The Role & Capability of Different Rocket Propulsion Systems

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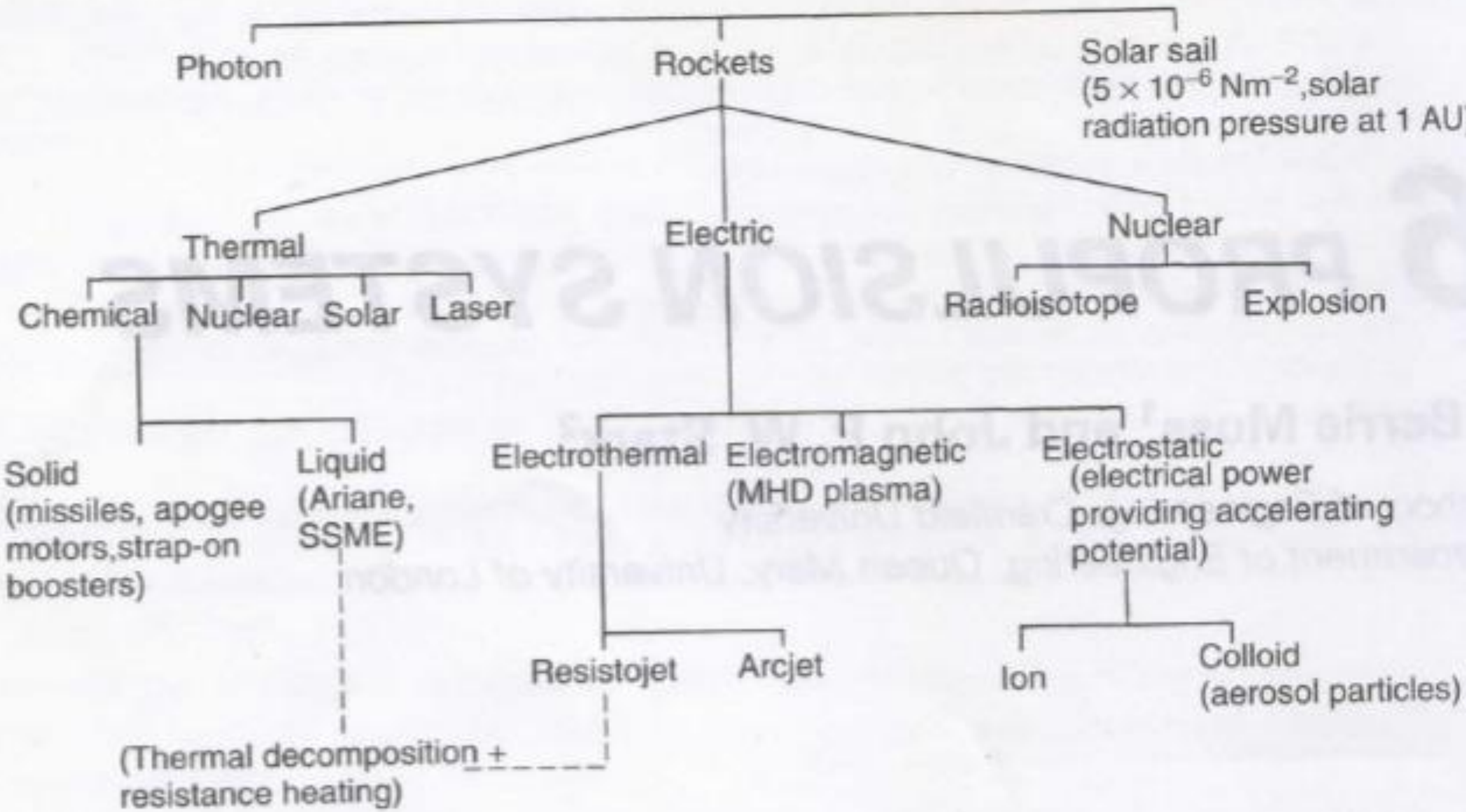


Figure 6.1 Propulsion systems classification

Classification of Spacecraft Propulsion Systems

- Electric: High exhaust velocity , low specific power or thrust acceleration
  - Power limited
- Nuclear or Chemical
  - High thrust acceleration but poor propellant utilisation due to their limited exhaust velocity

Classification of Spacecraft Propulsion Systems

- Mostly thermal and electric for practical devices
- Primary propulsion for launch vehicles is restricted to solid or liquid powered chemical rockets
- Solar sail – restricted due to the weak solar radiation pressure – 5×10^{-6} N/m^2

Classification of Spacecraft Propulsion Systems

- Nuclear – NERVA programme of the 1960's
- Nuclear engine for rocket vehicle applications
- Resulted in a ground-tested solid core (graphite) U235 fission-powered engine developing 300kN, Isp = 825s

Performance Parameters

- *Specific Impulse* $I_{sp} = \frac{F}{\dot{m}g}$
- = thrust/weight of fuel burnt per second
- Kinetic power of rocket exhaust P is given by:
- $P = \frac{1}{2}\dot{m}V_e^2$ Ve = exhaust velocity

Performance Parameters

- $F = \dot{m} V_e$
- Hence kinetic power $P = \frac{1}{2} F V_e$
- Vehicle acceleration $\alpha = \left(\frac{F}{g_o m}\right)$
- $F = m\alpha g_o$ α *is a multiplier of* g_o
- Specific power $\frac{P}{m} = \frac{1}{2} \alpha V_e g_o$

Distinguishing Performance Parameters

- $\frac{P}{m}$ = specific power
- V_e = exhaust velocity
- A = acceleration

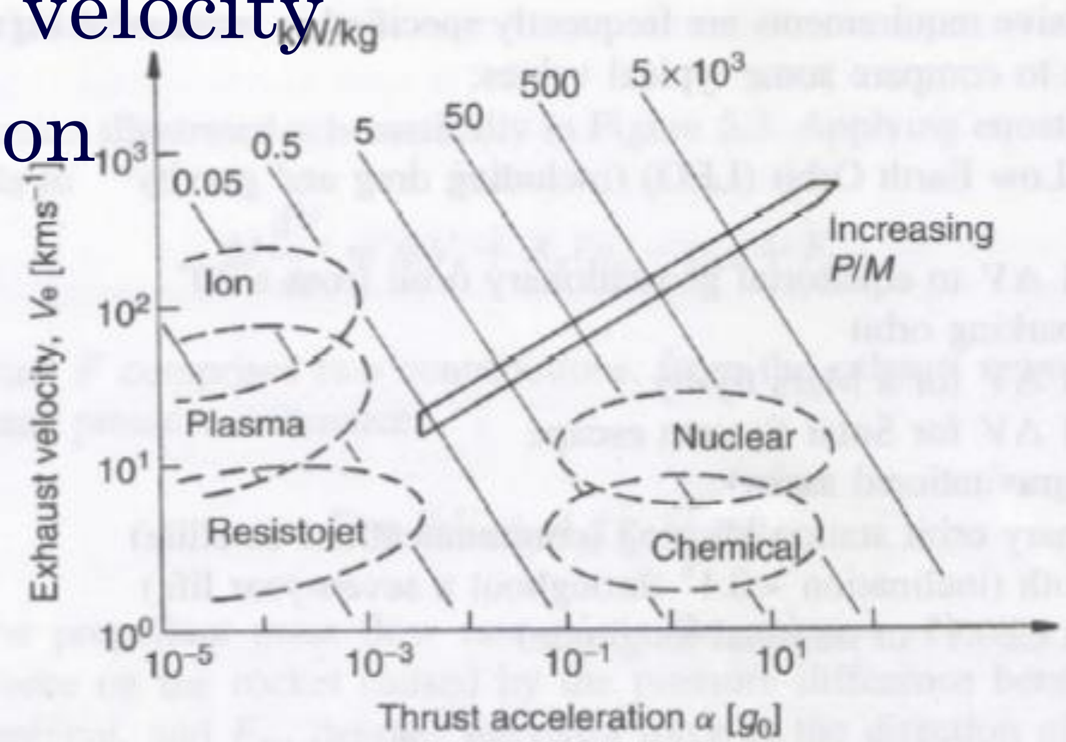
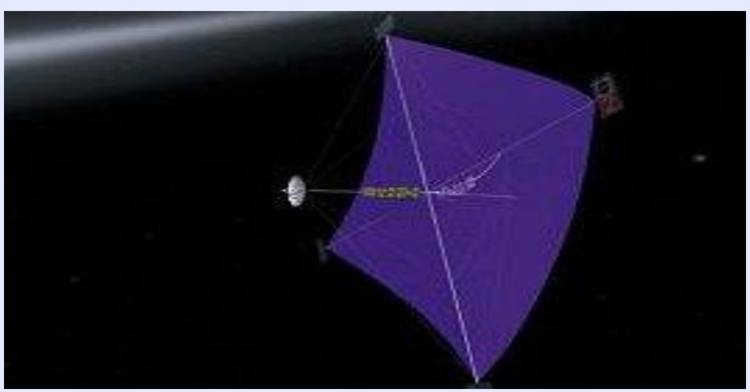
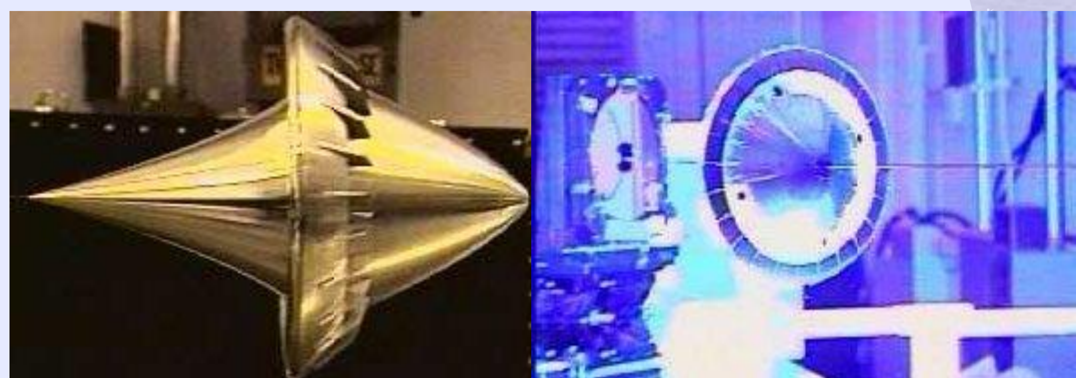


Figure 6.2 Comparative rocket performance

Comparison of Various Propulsion Techniques:

Type	Isp, s	Thrust, N	Comments
Chemical	~300	$\sim10^{6}$	Main space work horse to date
RAM/Rocket	?	?	Hypersonic Vehicle / single stage to orbit?
Nuclear	800	$\sim10^{6}$	Too dangerous to contemplate!!
Cold Gas	<100	<200	Simple, reliable, weak, attitude/orbit control
Ion Engine	~4000	$\sim 10^{-2}$	High Isp, fuel efficient, attitude/orbit control
MHD	~2000	~1	Plasma MHD , future development of ion eng.
Solar Sail	NA	10^{-3} /100m^{2}	Weak photon pressure. Only inner solar sys.
Laser	2000		Exotic, tried in laboratory (Lightcraft below)

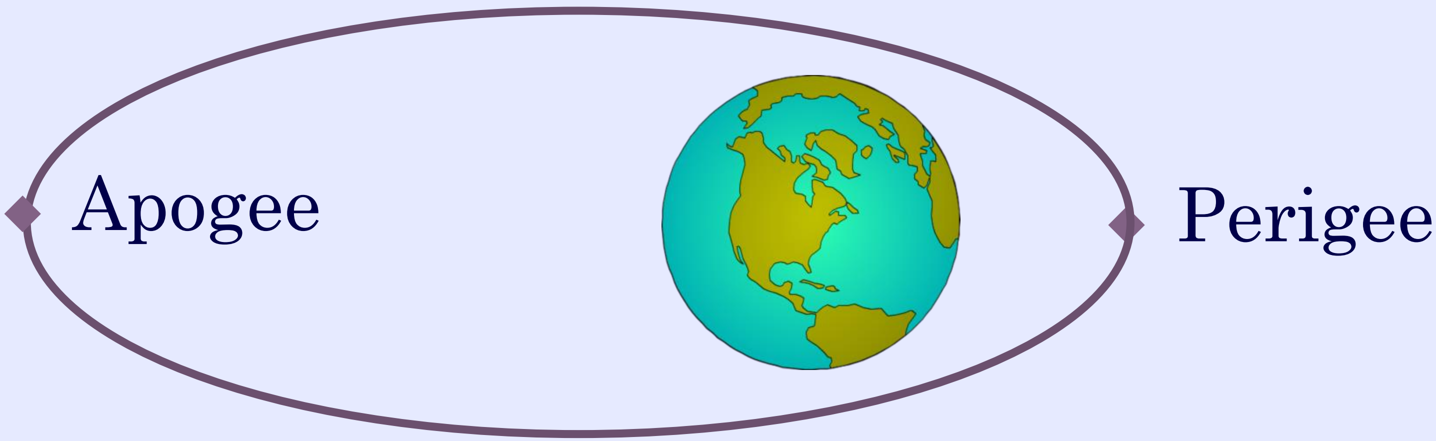

Solar Sail powered craft

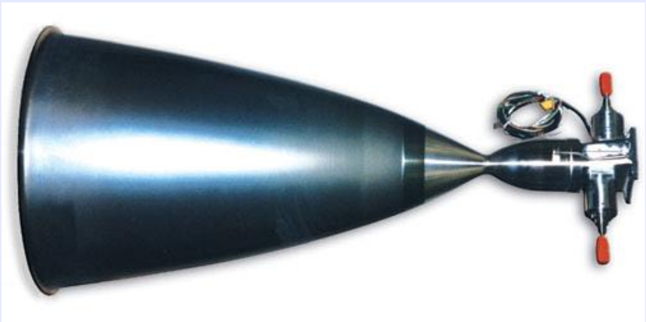

Laser propelled ‘Lightcraft’ – laboratory test

Why do we need propulsion systems?

- Launch Vehicles – main engines and strap on boosters
  - Continuous high level of thrust for minimum of 8 minutes. 2×10^6 N for each space shuttle main engine
- Apogee motors for space craft orbit circularisation and inclination removal
- Perigee motors for orbit raising – typically 75kN for approx 60 secs

Apogee - Perigee





400 N Bipropellant Apogee Motor
(model S400-15)

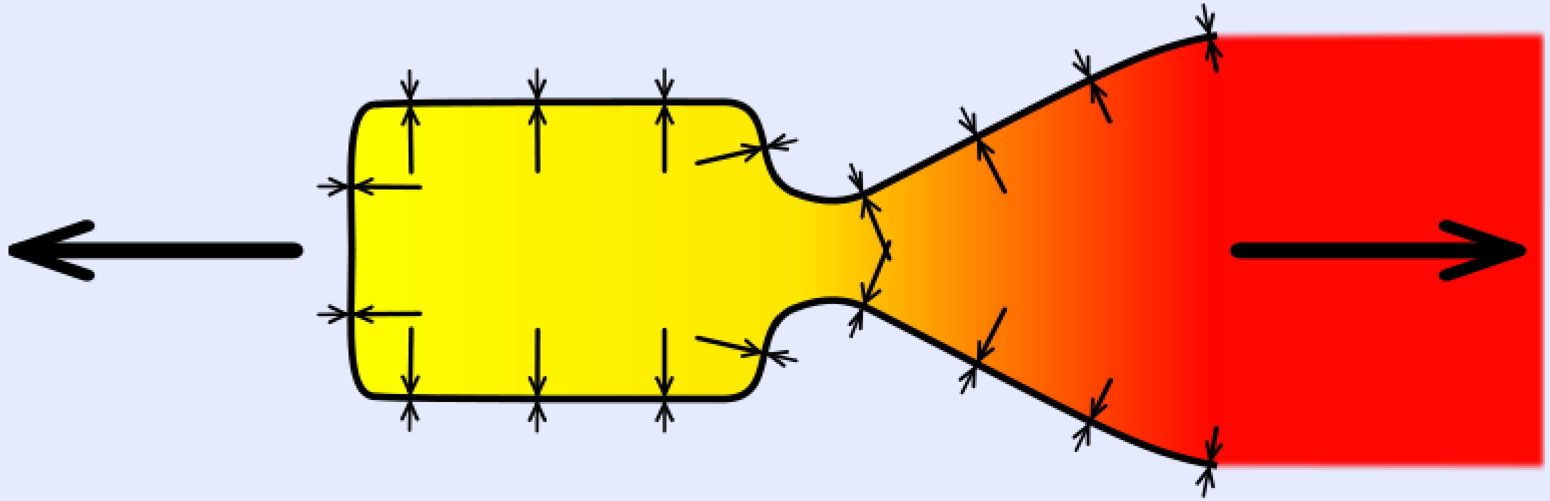
AIRBUS
DEFENCE & SPACE

Station keeping

- Spacecraft station keeping, altitude and orbit control – 10^{-3} N to 10 N
- Intermittent and pulsed operation over the complete duration of the mission

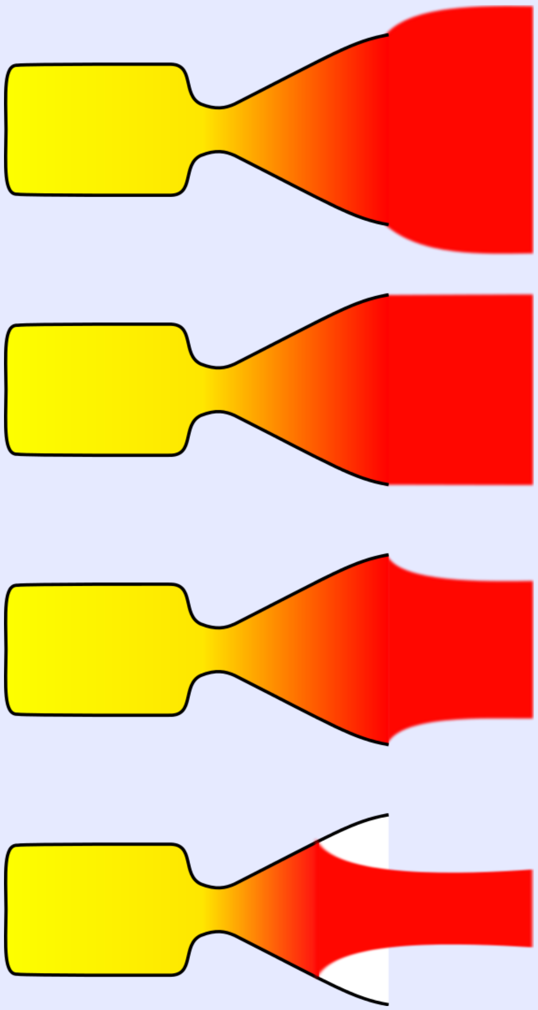
Convergent/Divergent nozzle

- Using a convergent/divergent nozzle gives more force since the exhaust also presses on it as it expands outwards, roughly doubling the total force.
- Note that the pumps moving the propellant into the combustion chamber must maintain a pressure larger than the combustion chamber -typically of the order of 100 atmospheres.

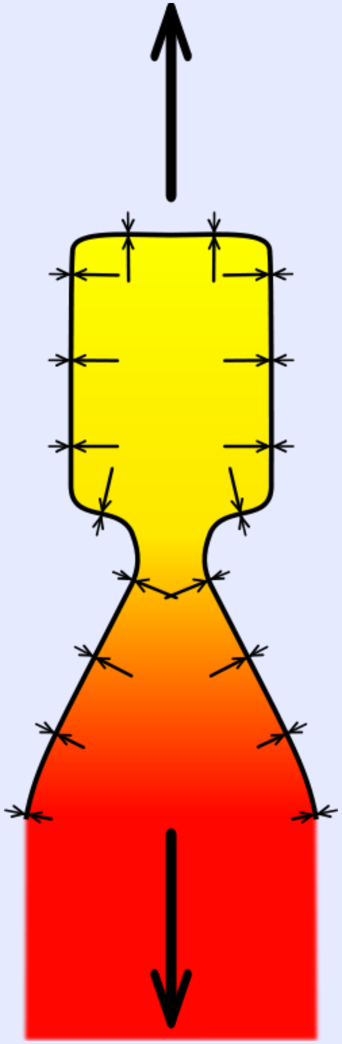


Convergent/Divergent nozzle

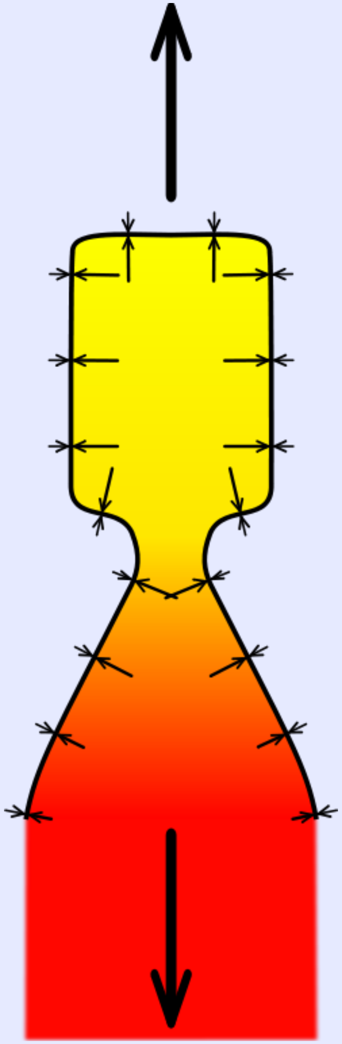
- Due to the supersonic nature of the exhaust jet the exit pressure can be different from the ambient atmospheric pressure.
- *Nozzles* are said to be (top to bottom):
  - **Underexpanded** (above ambient).
  - **Ambient**.
  - **Overexpanded** (below ambient).
  - **Grossly overexpanded**.
- If under or overexpanded then loss of efficiency occurs, grossly overexpanded nozzles lose less efficiency, but the exhaust jet is usually unstable.
- Rockets become progressively more underexpanded as they gain altitude.
- Note that almost all rocket engines are momentarily grossly overexpanded during startup in an atmosphere.

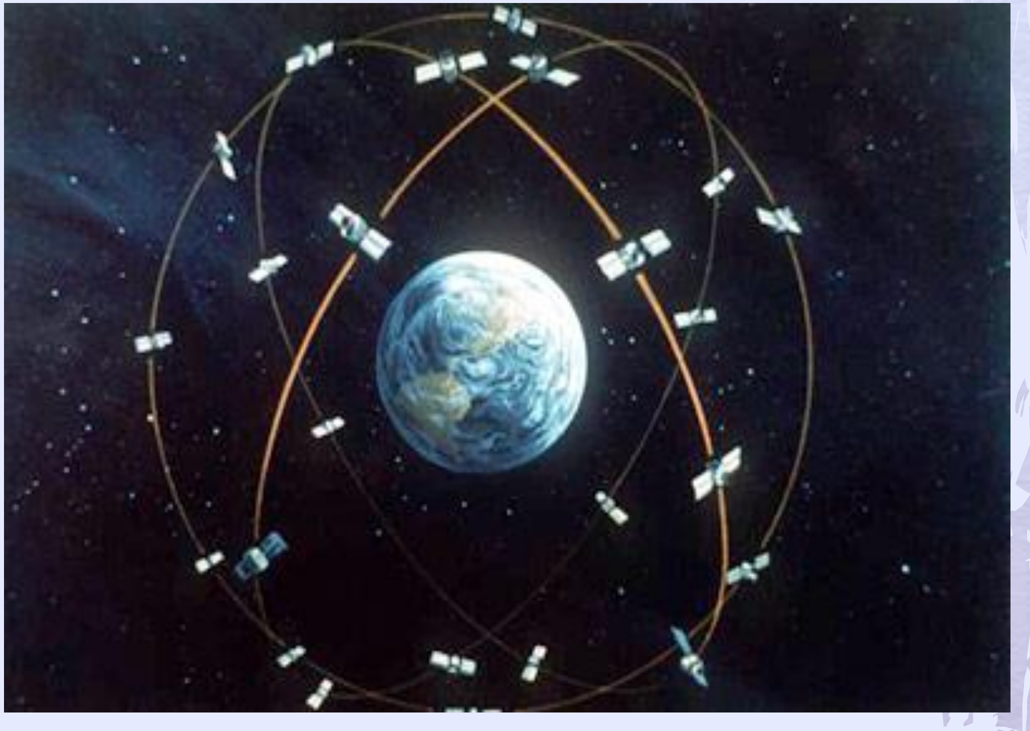


This is the only way into space, its fundamental technology



You can't have satellites without it





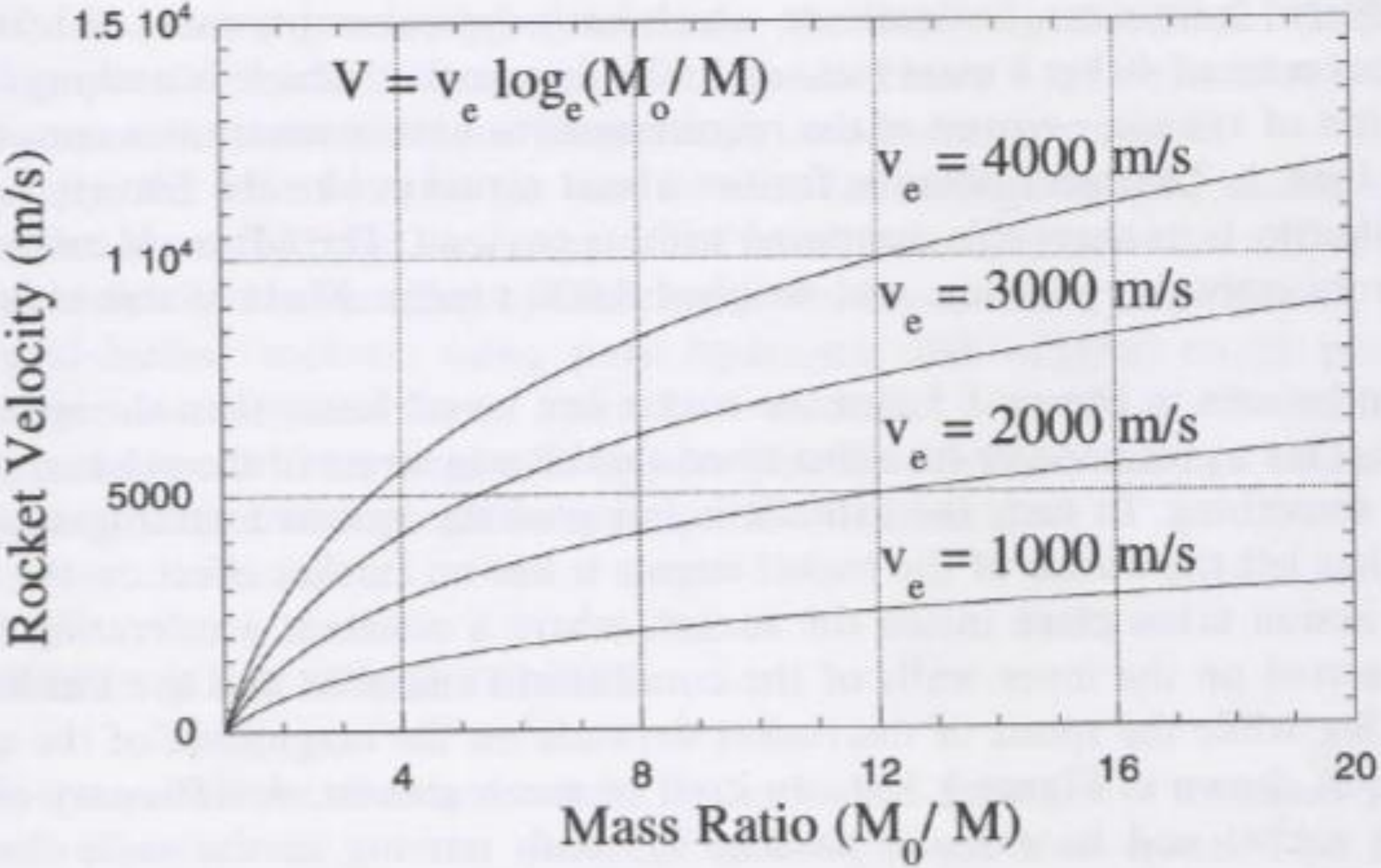
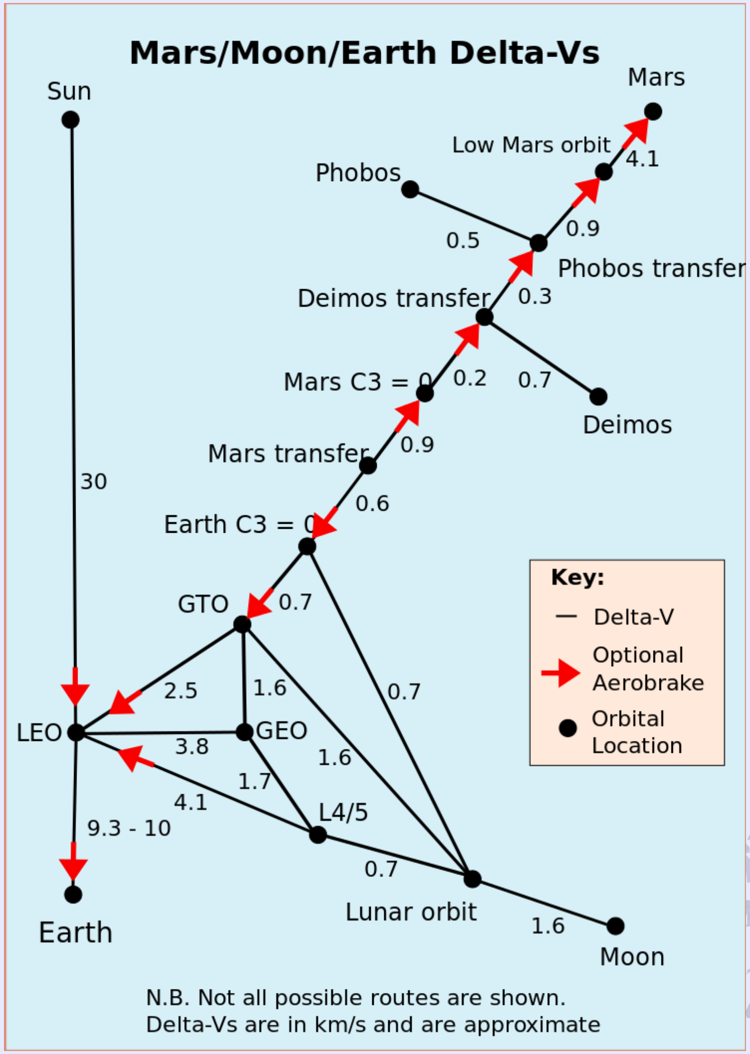


Figure 1.2. Tsiolkovsky's rocket equation.

Delta-v's from the Rocket Equation

- A map of approximate Delta-v's around the solar system between Earth and Mars
- The required delta-v can also be calculated for a particular manoeuvre; for example the delta-v to launch from the surface of the Earth to Low earth orbit is about 9.7 km/s
- $\Delta v = v_e ln \frac{m_o}{m}$



Thermodynamics

$$V_e = \left\{\frac{2\gamma}{\gamma-1}\frac{R_o}{MW}T_o\left[1-\left(\frac{P_e}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} \quad ; \quad U_e \, or \, V_e = c^* C_F^o$$

$$C_F^o = \left\{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{P_e}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}}$$

$$\frac{A_e}{A^*} = \left\{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{P_e}{P_o}\right)^{\frac{1}{\gamma}}\right\}/C_F^o; \qquad \frac{A_e}{A^*} = \frac{1}{M_e}\left\{\left(\frac{2}{\gamma+1}\right)\left[1+\frac{\gamma-1}{2}M_e^2\right]\right\}^{\frac{\gamma+1}{2(\gamma-1)}}$$

$$\frac{\dot{m}}{A} = P_o\left\{\frac{2\gamma}{(\gamma-1)}\frac{1}{RT_o}\left(\frac{P}{P_o}\right)^{\frac{2}{\gamma}}\left[1-\left(\frac{P}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} \quad ;$$

$$A = \frac{\dot{m}}{P_o}\left\{\frac{2\gamma}{(\gamma-1)}\frac{1}{RT_o}\left(\frac{P}{P_o}\right)^{\frac{2}{\gamma}}\left[1-\left(\frac{P}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{-\frac{1}{2}}$$

$$F = \dot{m}V_e + (P_e + P_a)A_e$$

$$F = P_o A^*\left\{\frac{2\gamma^2}{(\gamma-1)}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_e}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} + (P_e + P_a)A_e$$

Design

- The main contribution from thrust comes from the mass flow rate – mostly determined by the throat area and combustion chamber pressure
- The product $P_o A^*$ is a fixed parameter which determines the size and general mechanical design of the Rocket engine
- A^* fixes the overall dimensions
- P_o fixes the strength of the walls, pump capacity and dimension

Expansion Ratio

- $\frac{A_e}{A^*}$ is very important - some times called the expansion ratio
- $\frac{A_e}{A^*} \cong 10$ for the first stage motors for use in low atmosphere
- $\frac{A_e}{A^*} \cong 80$ for high altitude and space
- For maximum efficiency $P_e = P_a$ and the value of P_e is determined by the expansion ratio

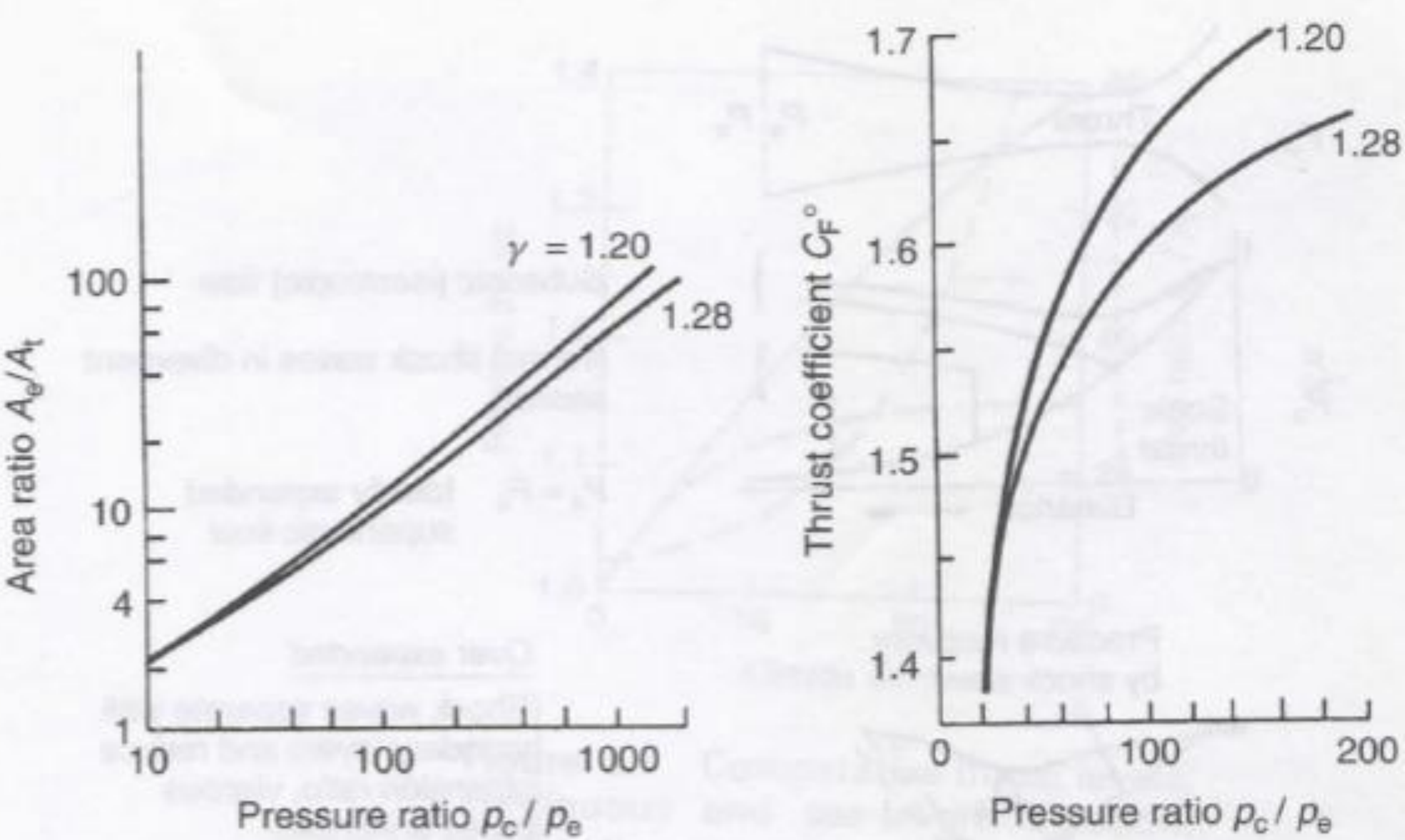


Figure 6.5 The variation of area ratio and thrust coefficient with pressure ratio

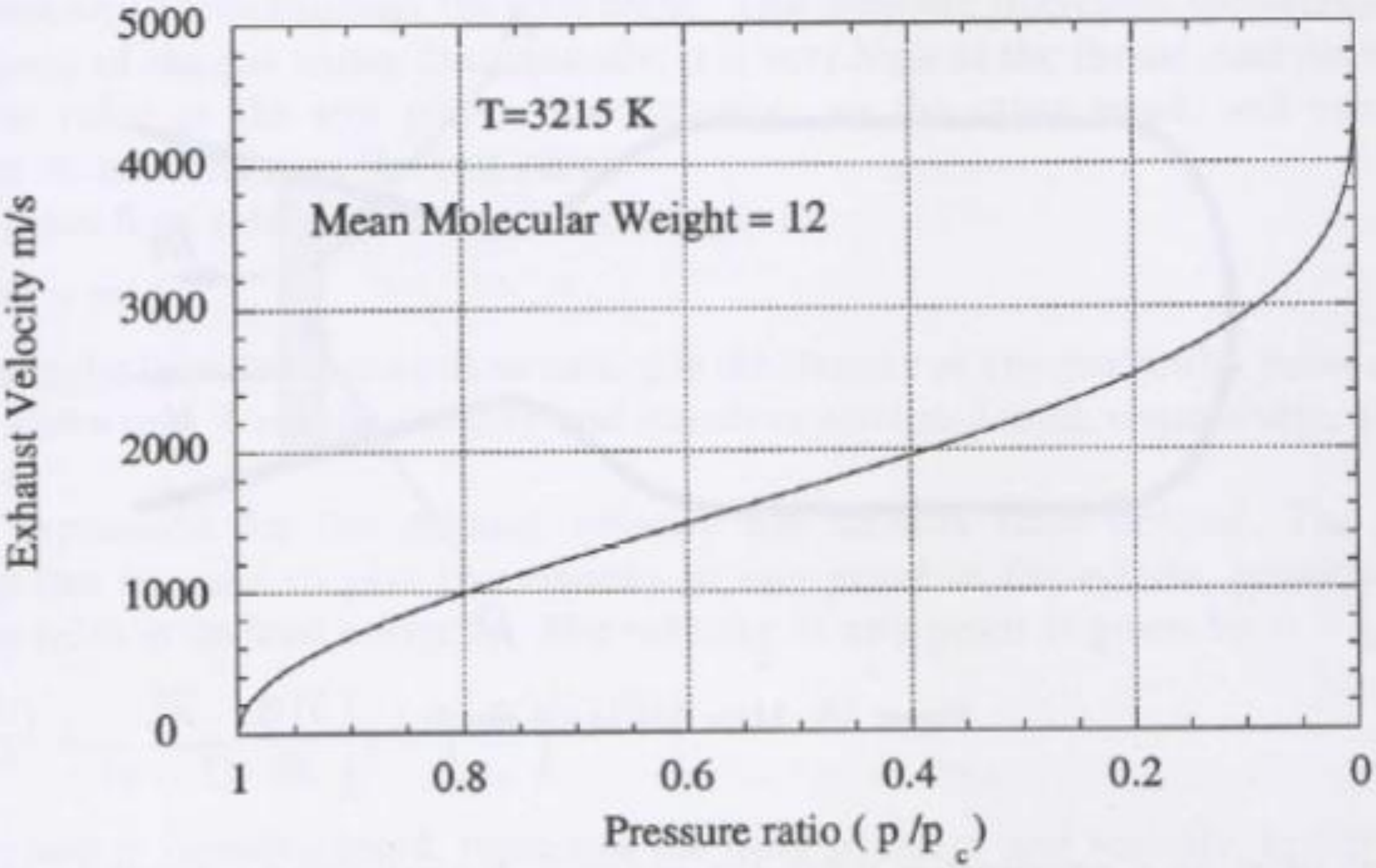


Figure 2.7. Gas velocity as a function of the pressure ratio.

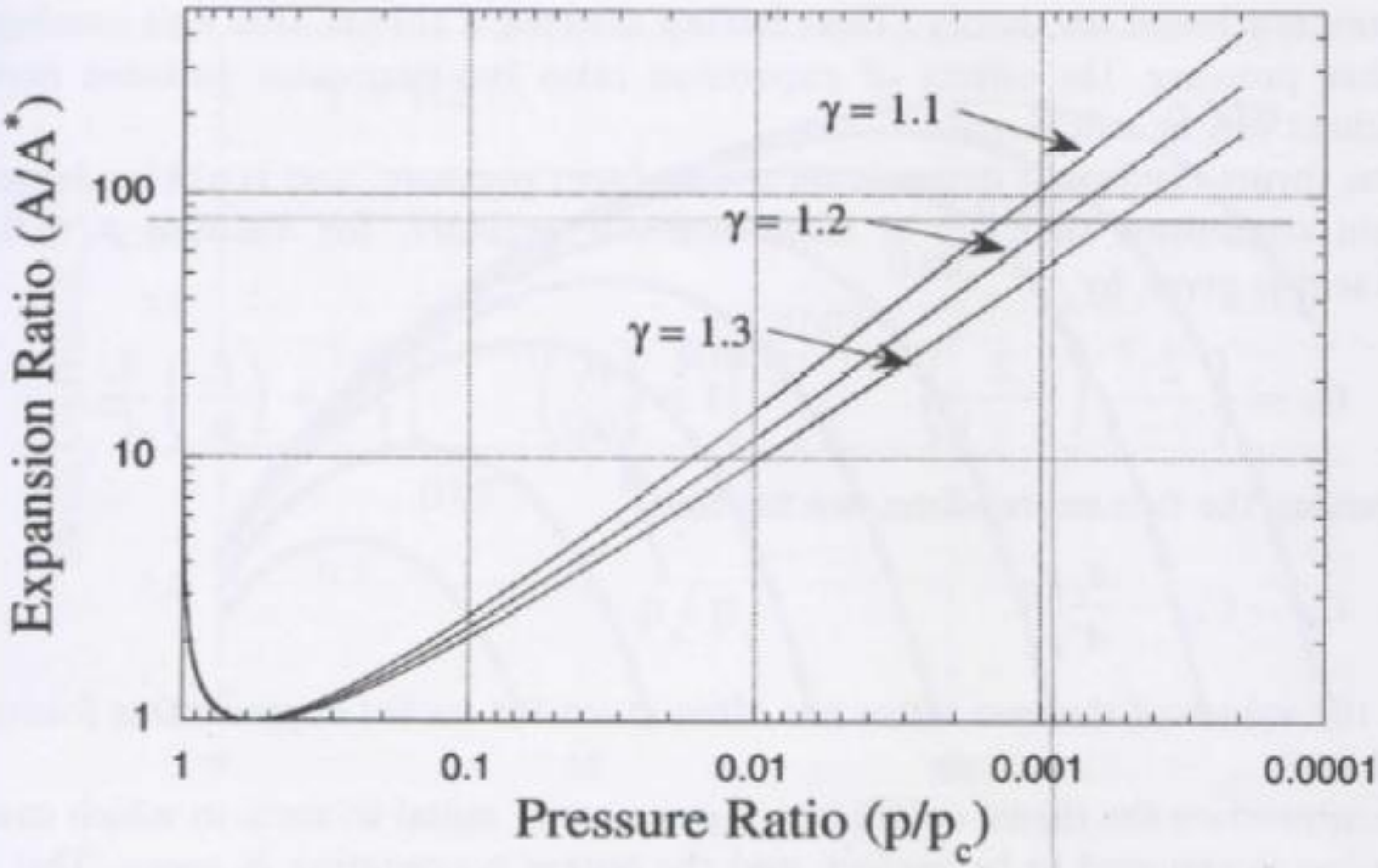


Figure 2.11. Expansion ratio as a function of the pressure ratio for changing γ.

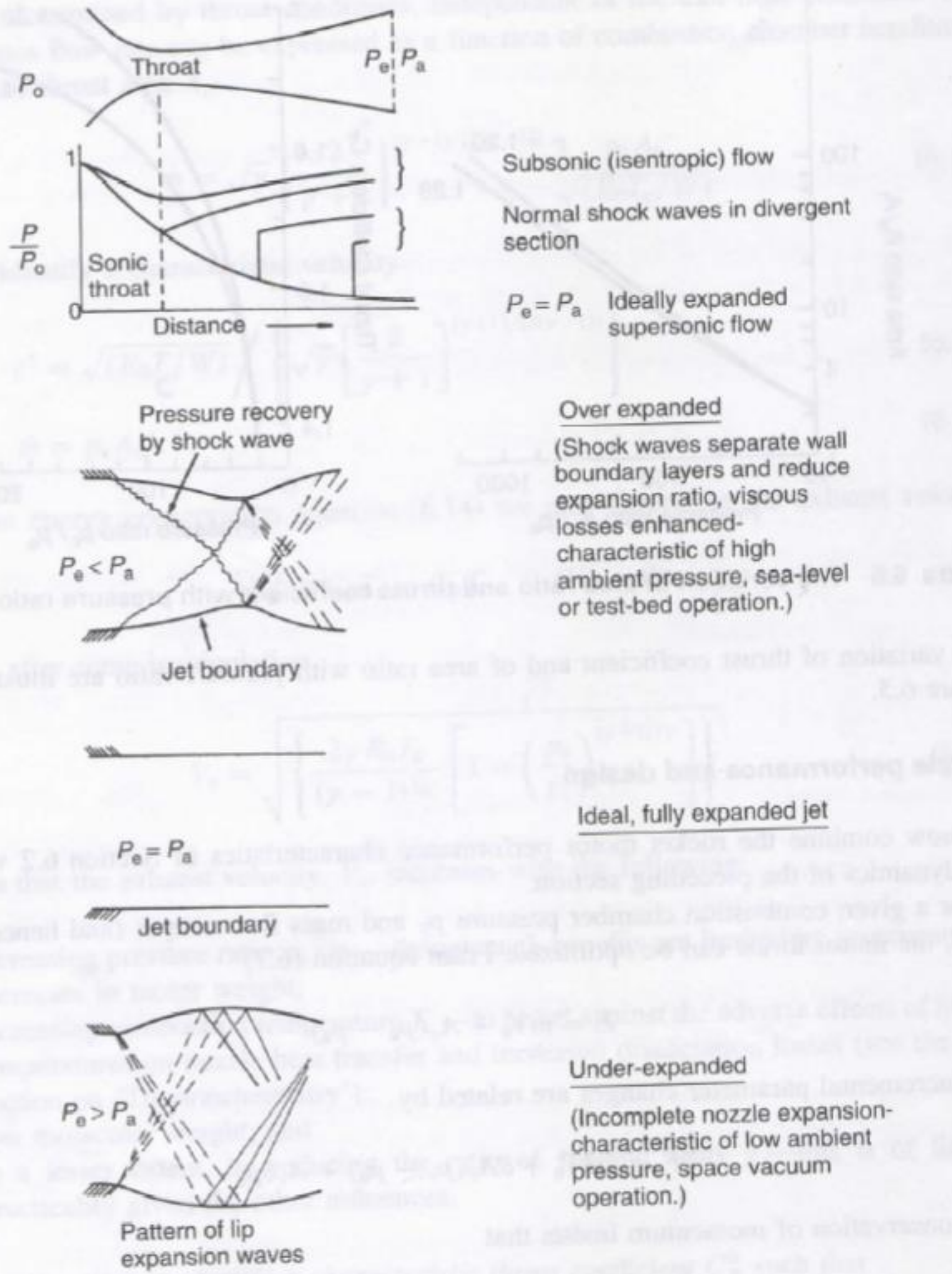


Figure 6.6 Nozzle flows: non-ideal expansion

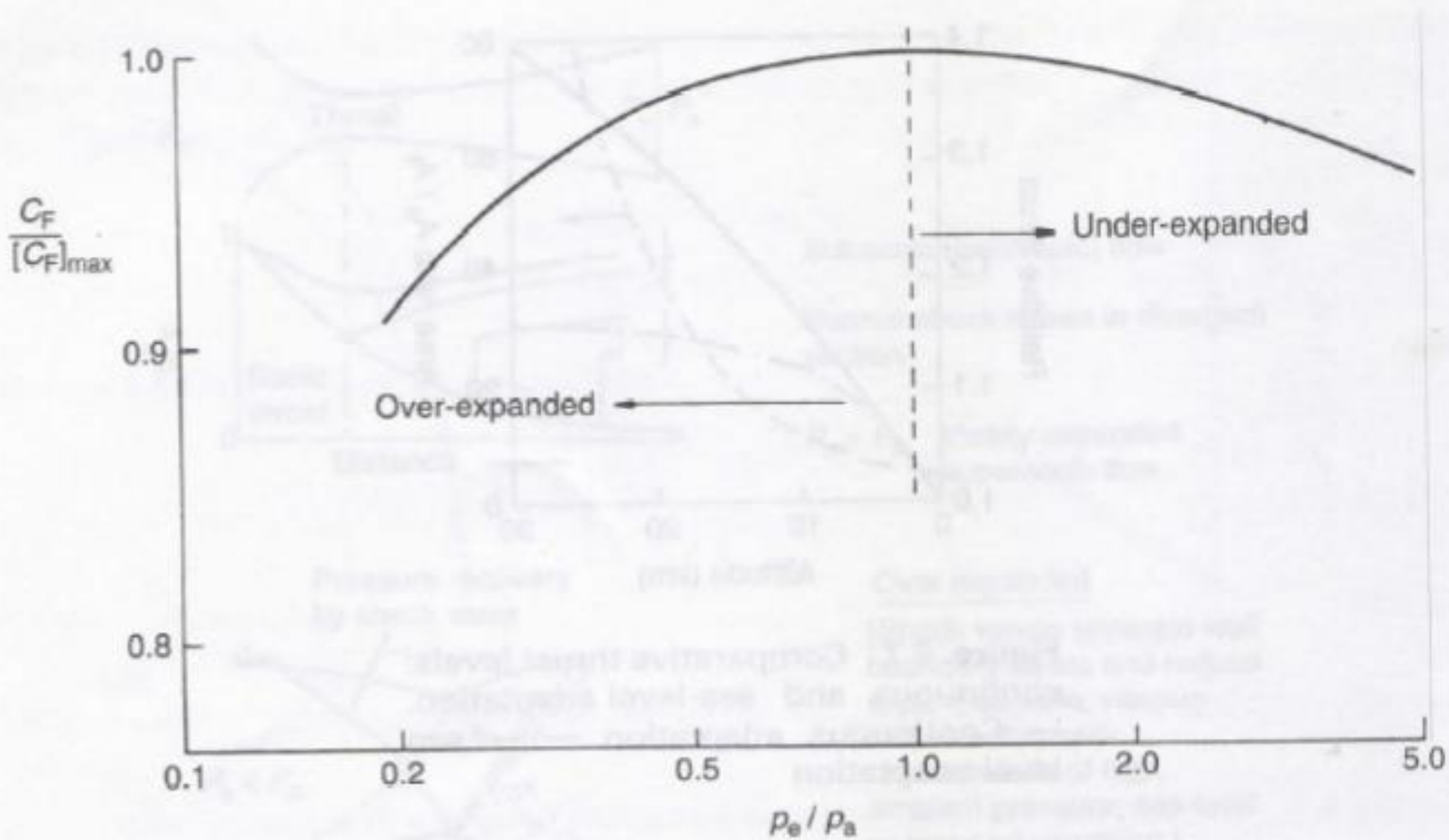


Figure 6.8 The effect on thrust coefficient of departures from ideal expansion

Thrust Coefficient & Characteristic Velocity

- The thrust Coefficient tells us about the performance of the nozzle
- The Characteristic Velocity tells us about the performance of the propellant
- $C_F = \dfrac{Thrust}{Chamber\ pressure\ X\ throat\ area} = \dfrac{F}{P_o\, A^*}$

$$C_F = \left\{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_e}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} + \left\{\frac{P_e}{P_o} - \frac{P_a}{P_o}\right\}\frac{A_e}{A^*}$$

Thrust Coefficient

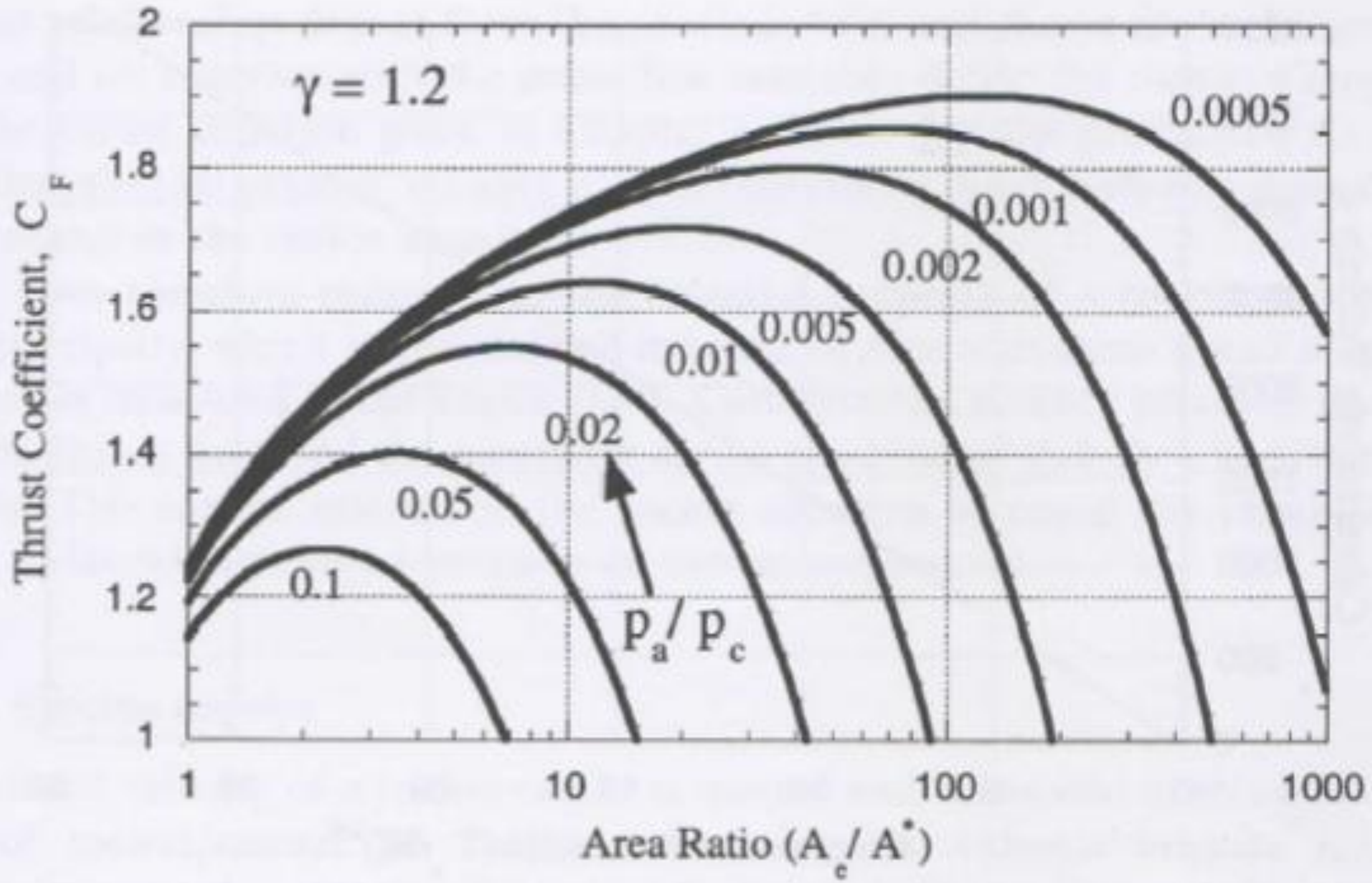


Figure 2.12. Thrust coefficient plotted against expansion ratio for different atmospheric pressures.

Thrust Coefficient

- For any value of P_a , C_F peaks at a particular expansion ratio
- The area expansion ratio at which this occurs is that which equates the exit and ambient pressures

Characteristic velocity c^*

- The Characteristic velocity c^* measures the efficiency of conversion of thermal-to-kinetic energy
- $c^* = \frac{Force}{mass\ flow} = \frac{P_o}{\dot{m}} A^*$
- A typical value of characteristic velocity is around 2000 m/s for LOx – LH_2 and 1500 m/s for solid fuel propellants

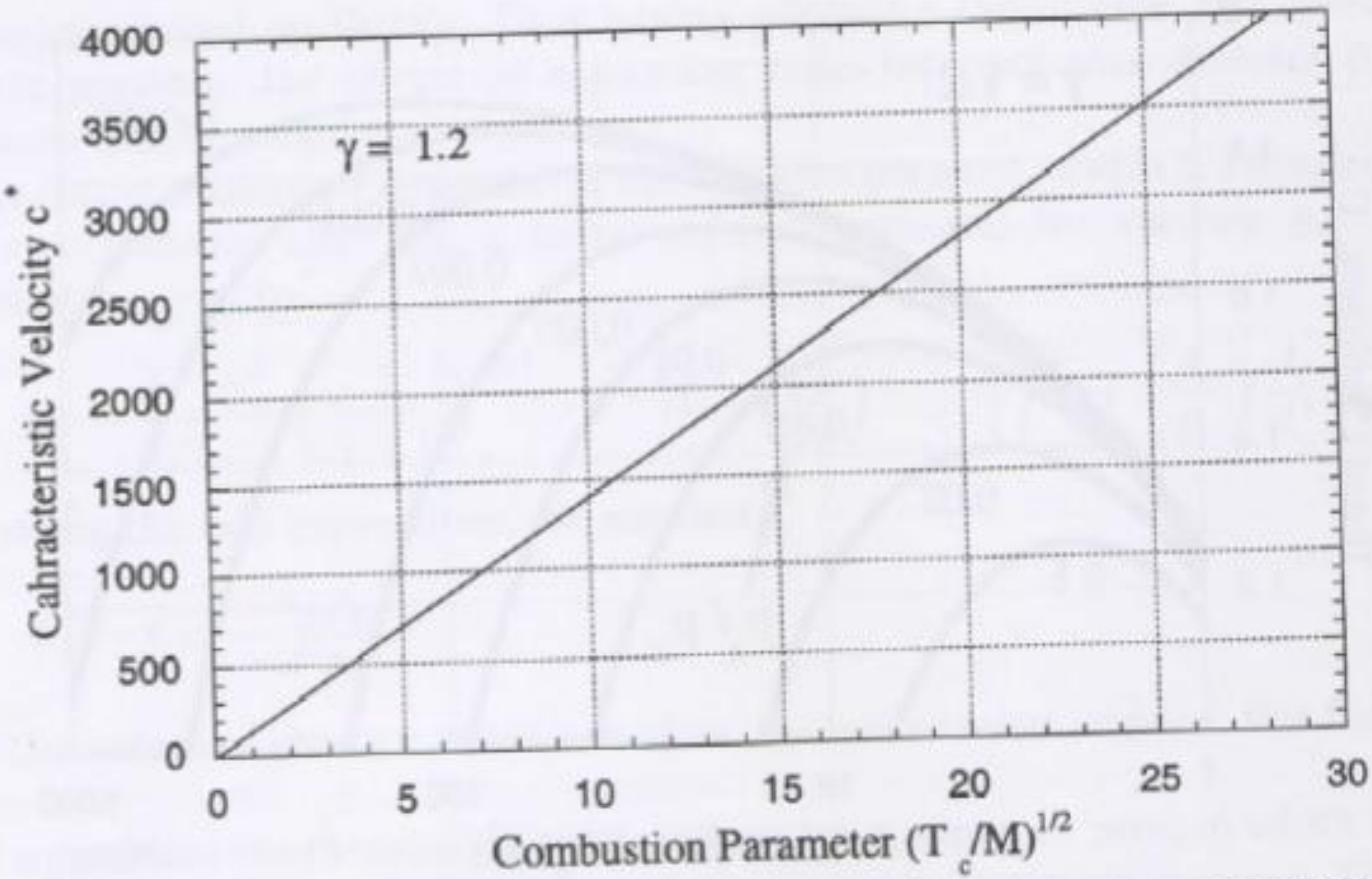


Figure 2.13. Characteristic velocity as a function of the combustion temperature and molecular weight.

For high c^* ; T_c should be high M should be low

Chemical Rockets : Liquid Propellants

Advantages: easy to control/throttle, often restartable, high Isp, thin wall tanks provide high MR, guidance of vehicle by gimballing thrust chamber

Disadvantages: Often cryogenic, toxic, difficult to handle propellants, few propellants environmentally friendly, complex systems → lower reliability

Main Types: (1)Bi-propellant (2) Mono-propellant & (3) Hybrid (liquid/solid)

Bi-Propellant Rockets:

Oxidizer/Fuel	Isp(s)	Example Launch Systems
LOX / RP-1	350	Atlas, Delta, N1, Vostok, Soyuz, Zenit. cryogenic
N_2O_4 / N_2H_4	~320	Titan, Ariane4, Shuttle OMS, Proton. storable, toxic,hypergolic
LOX / LH	450	Shuttle, Ariane 5, Saturn V, Centaur cryogenic, clean→H_2O

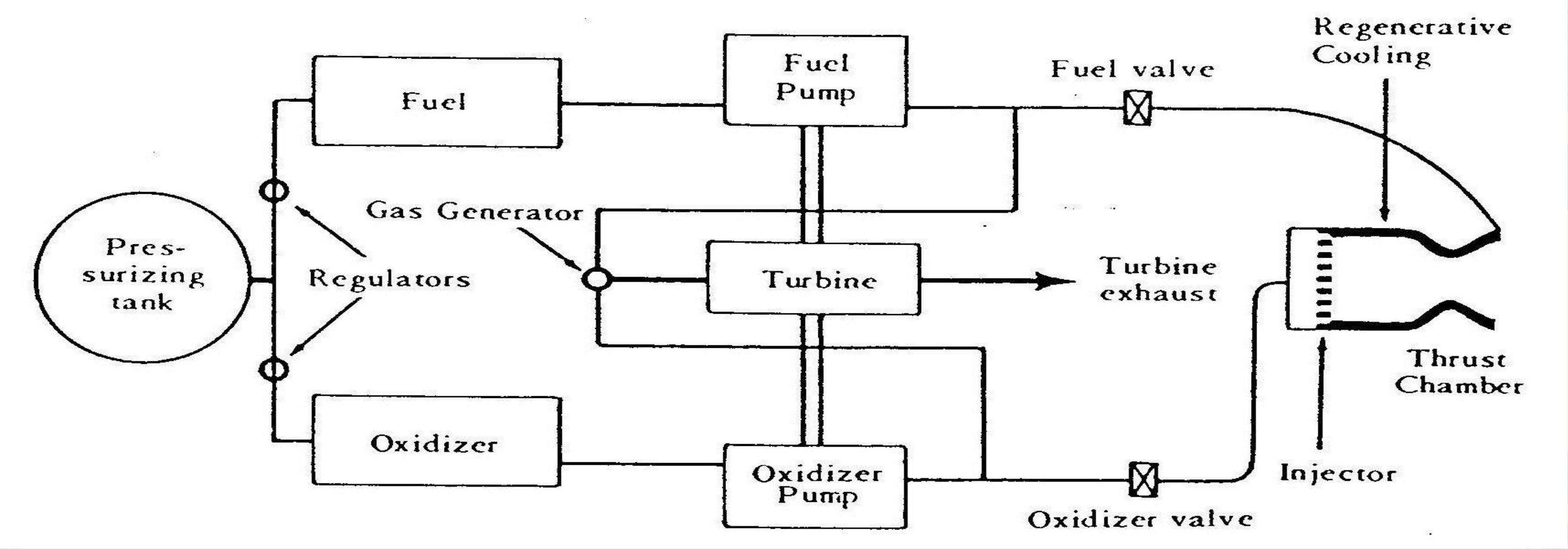
Uses: Most satellites/spacecraft launched by bi-propellant main stages

Comparison of viable liquid propellant combinations

Fuel	Oxidizer	Molecular weight W products	Combustion temperature T_c (K)	Ideal specific impulse I_{sp} (s)	Mean density ρ (kg/m^3)
H_2 (hydrogen)	O_2 (oxygen)	10	2980	390	280
	*F_2 (fluorine)	12.8	4117	410	460
Kerosene	O_2	23.4	3687	301	1020
	F_2	23.9	3917	320	1230
	RFNA (red fuming nitric acid)	25.7	3156	268	1355
	N_2O_4 (nitrogen tetroxide)	26.2	3460	276	1260
	H_2O_2 (hydrogen peroxide)	22.2	3008	278	1362
N_2H_4 (hydrazine)	O_2 (oxygen)	19.4	3410	313	1070
	*HNO_3 (nitric acid)	20	2967	278	1310
UDMH $(CH_3)_2NNH_2$ unsymmetrical dimethyl (hydrazine)	O_2 (oxygen)	21.5	3623	310	970
	*HNO_3 (nitric acid)	23.7	3222	276	1220
	*hypergolic				
Monopropellants					
N_2H_4		10.3	966	199	1011
H_2O_2		22.7	1267	165	1422

All quoted values are for $p_c = 7$ MPa with an ideal expansion to $p_e = 0.1$ MPa. Higher chamber pressures admit increases in I_{sp}—for example, at 20 MPa, LH_2–LOX yields a specific impulse of ~460 s.

Bi-Propellant Rocket System:



Propellant tanks usually lightly pressurized to get propellants to pumps. Tanks often thin walled- need pressure to stand up!

Pumps increase pressure to inject into thrust chamber, >chamber pressure

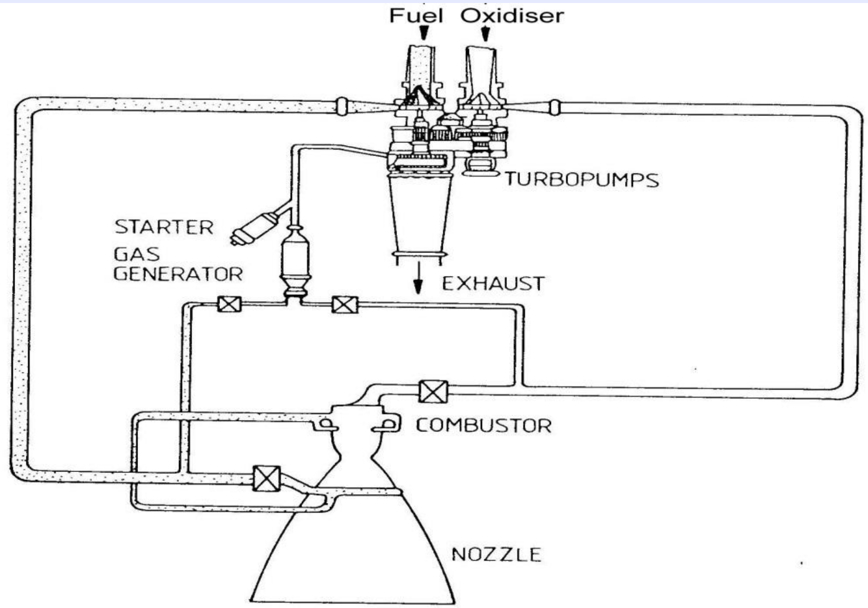
Turbine drives pumps. Turbine driven by gas generator or expansion of coolant

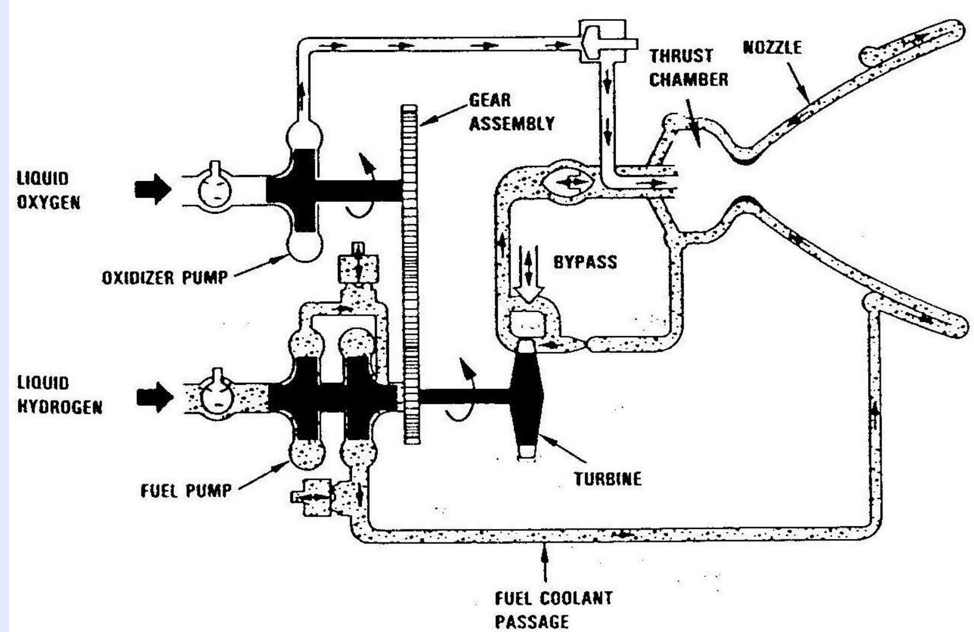
Thrust Chamber needs cooling- often regeneratively cooled- one propellant passes through channels in walls prior to injection. Nozzle=tubes brazed together.

Injector Assembly designed to finely atomise liquid & maximise mixing

Gimballing (small movement in angle of) thrust chamber relative to rest of vehicle permits control of vehicle direction

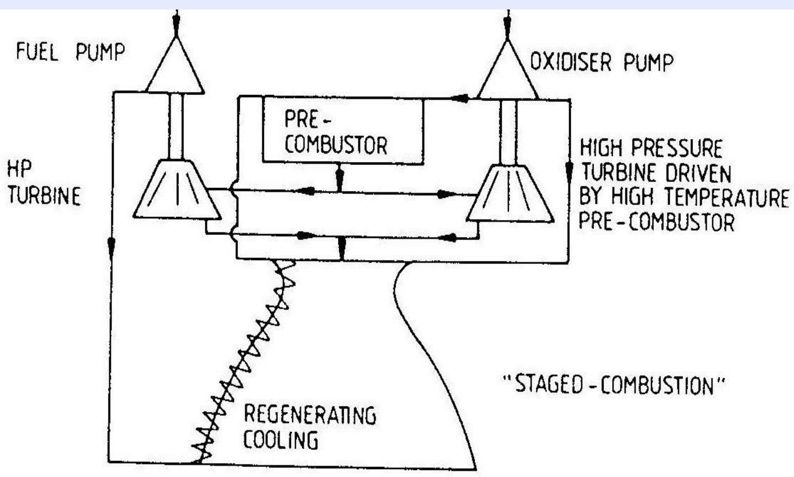
Pump Drives : Open, Closed, & Precombustion Systems





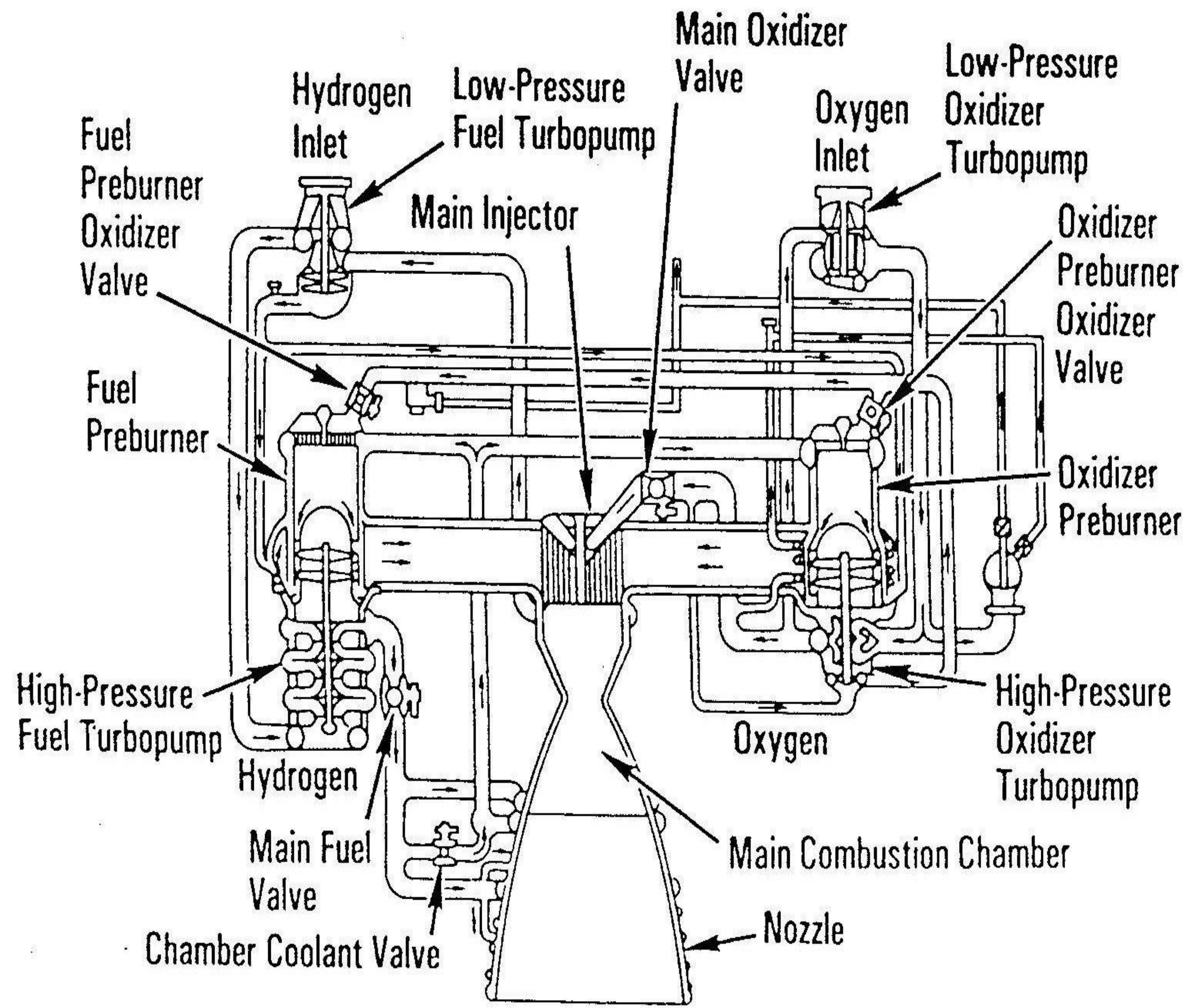
Open System: Turbine driven by gas generator using initial solid starter, then actual propellants. Turbine exhaust dumped alongside nozzle

Closed System: Low pressure turbine driven by expansion and vaporisation of propellant as it cools the thrust chamber



Pre-Combuster System: some fuel & oxidiser pre-combusted to drive high pressure turbine before entry into main thrust chamber

Shuttle Main Engine: one of three LOX / LH engines



Plumbing!!!Very complex, but basically a pre-combustion design

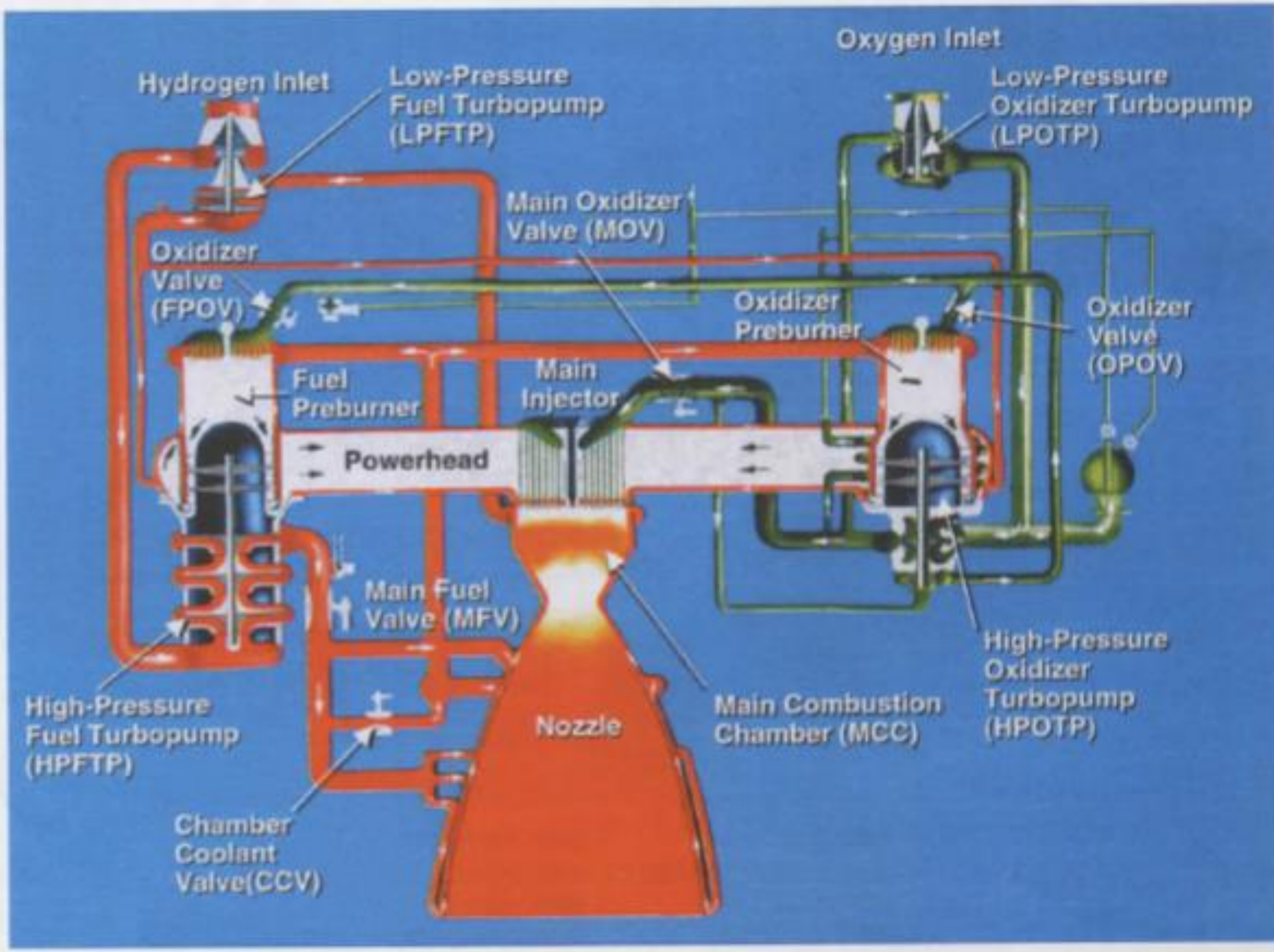


Figure 3.8. The Space Shuttle main engine.

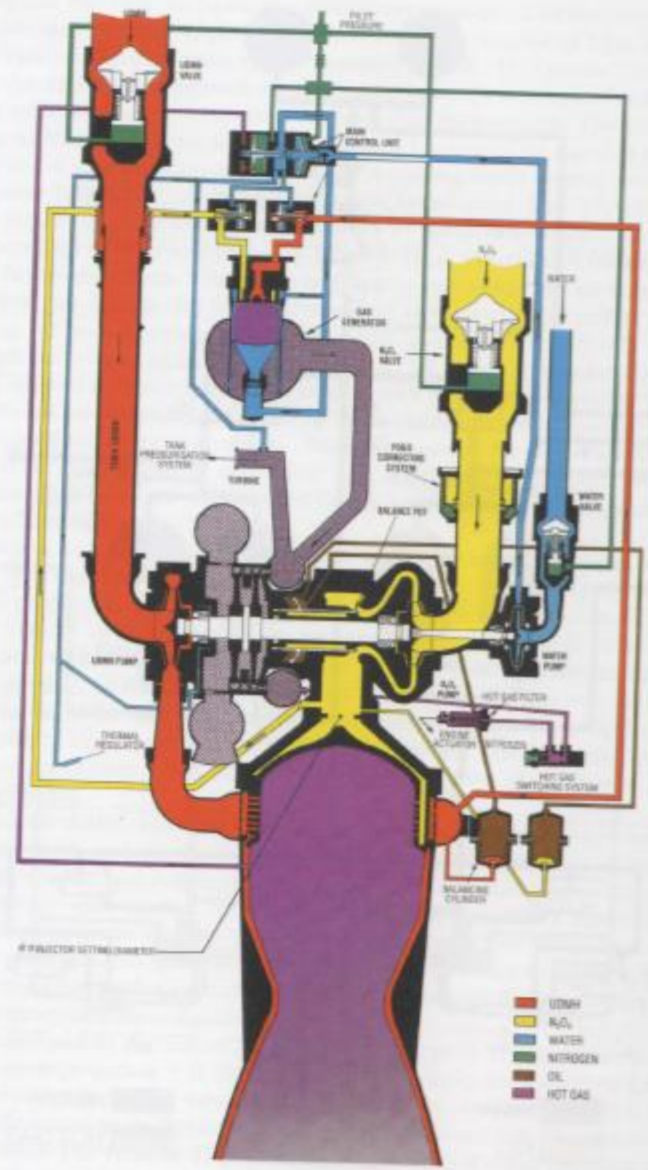


Figure 3.6. The Ariane Viking engine.

Chemical Rockets: Solid Propellant

Advantages: Simple, reliable, easy to add on to vehicle (strap on boosters).

Disadvantages: difficult to control, lower Isp than liquid propellant, heavy pressure container (low MR), environmentally unfriendly exhaust products.

Typical Propellants: Oxidizer & Fuel held together in rubber/asphalt/polybutadiene

Oxidizer- Ammonium Perchlorate, Fuel-Aluminium powder + hydrocarbons

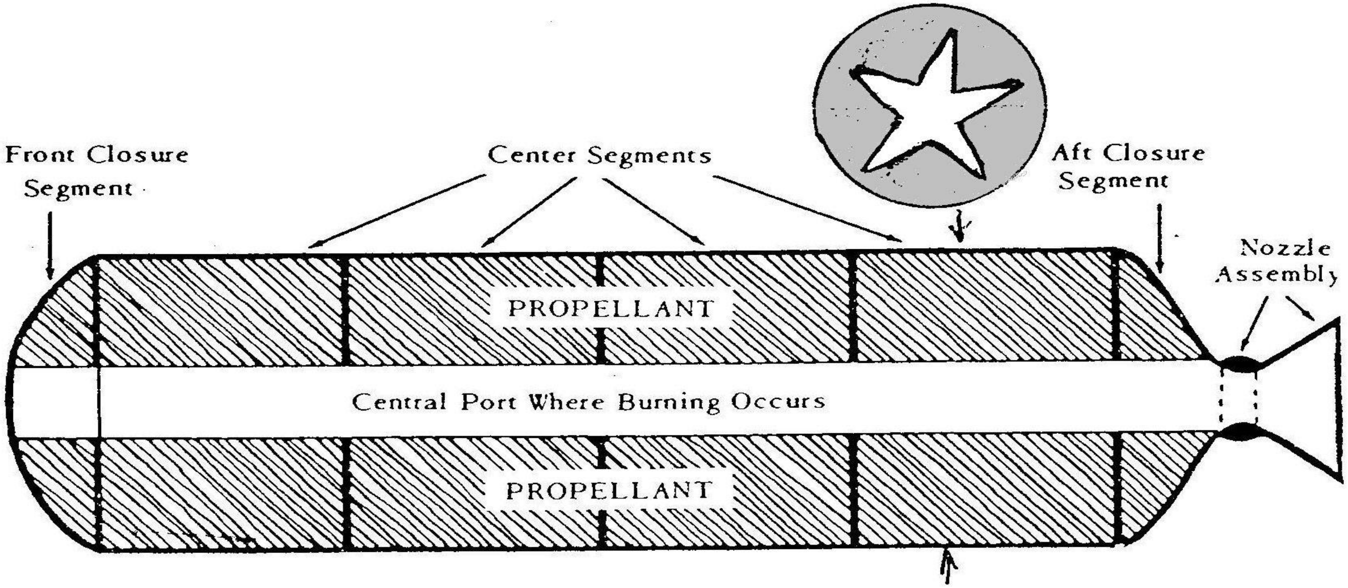
Typical Uses:

1)Add on first stage/booster to main liquid stage(Shuttle, Delta, Ariane,etc)

2) Apogee kick motors within spacecraft (to convert transfer orbit to GEO)

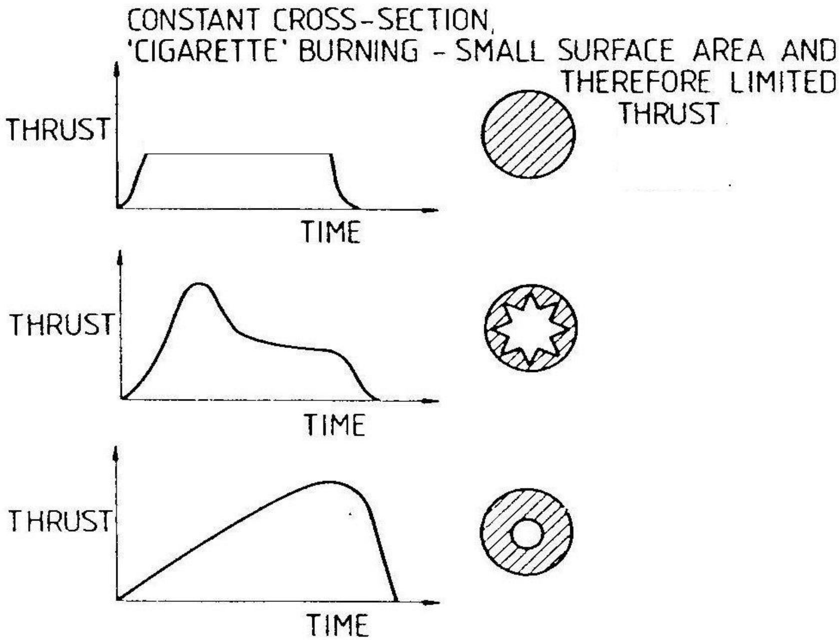
3) A few complete launch systems, Scout, Pegasus, Taurus

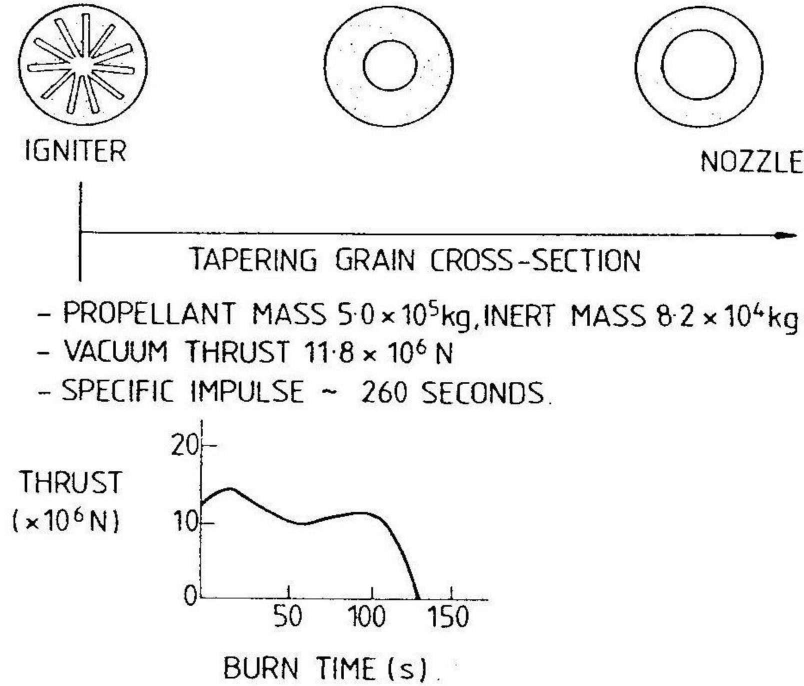
Simplified Typical Solid Rocket with cross section &
Delta launch with strap on boosters:

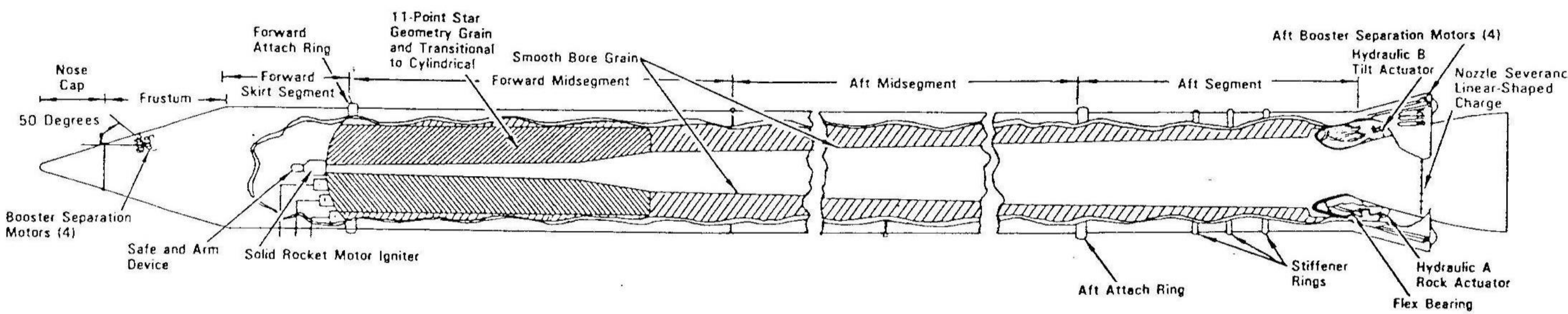


Varying Grain Geometries: Example of the Shuttle Solid Boosters

Cross-Sections: Star shape common- increases combustion area- increases F
Tapered changes-> F versus time curve







Need bonding agents and burn inhibitors at walls, Large solids need to be built in sections-> difficulties at joins (Challenger!) and at nozzle throat (esp. if gimballed)

Ariane

Mono-propellant Rockets

Advantages: Simpler than bipropellants, reliable, easy to restart (catalysts), small engine- easy to manufacture

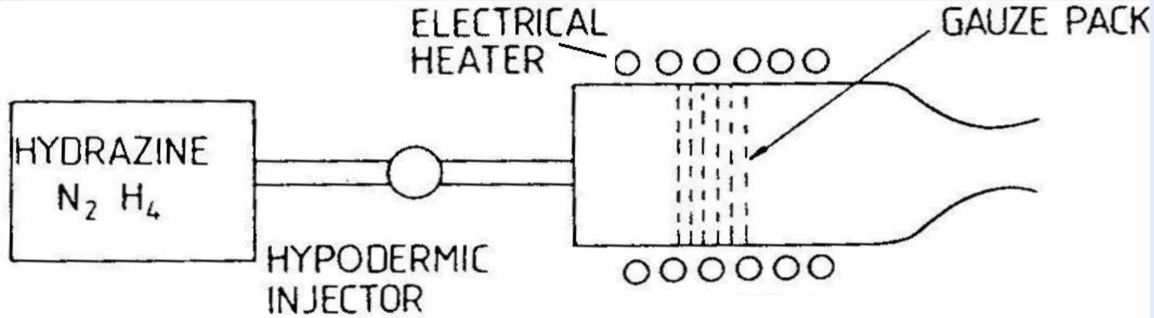
Disadvantages: Low Isp (<200s) low performance, → not used for launcher

Uses: Primarily in spacecraft as attitude control / orbit correction

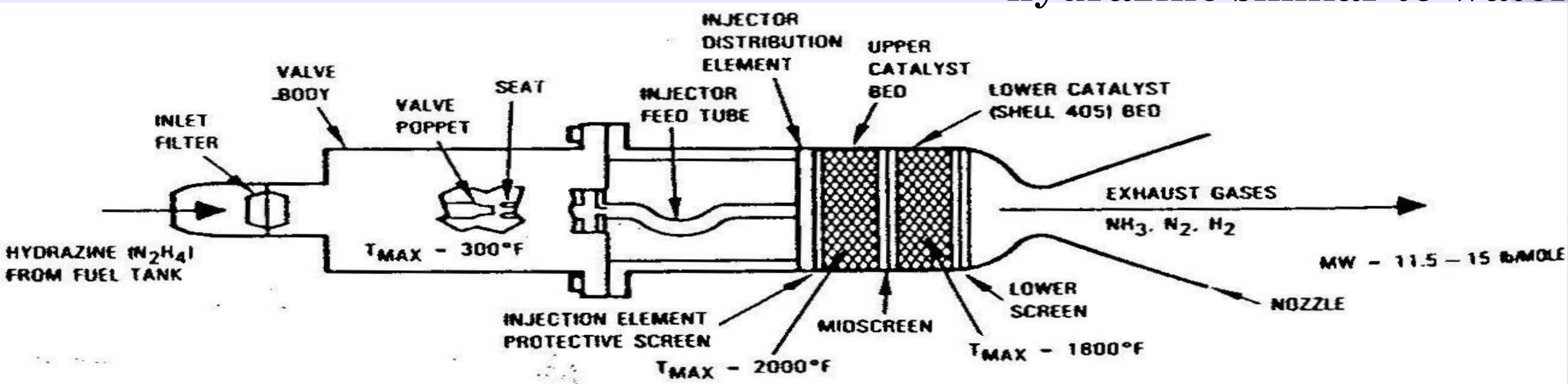
Typical Propellants:

1) N_2H_4 (hydrazine) + Al/Ir catalyst → hot gases NH_3, N_2, H_2

2) H_2O_2(hydrogen peroxide) + $KMnO_4$ catalyst → hot gases H_2O, O_2

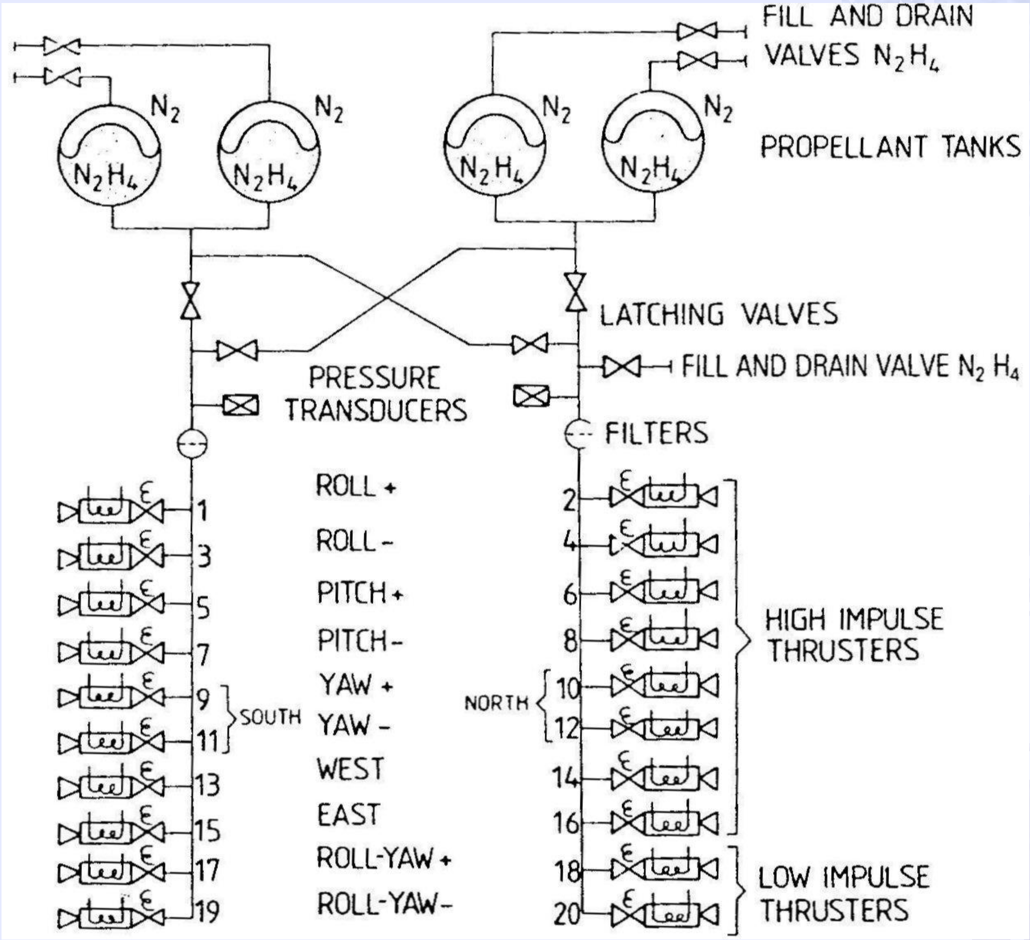


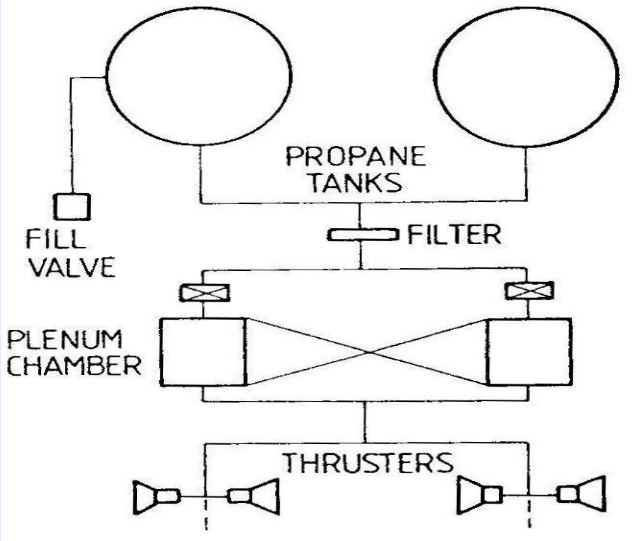
Propellant fed under pressure to catalyst→ exothermally decomposes → hot gas.
Stored liquid properties of hydrazine similar to water



Simple Spacecraft Attitude / Orbit Control via Monopropellant Thrusters

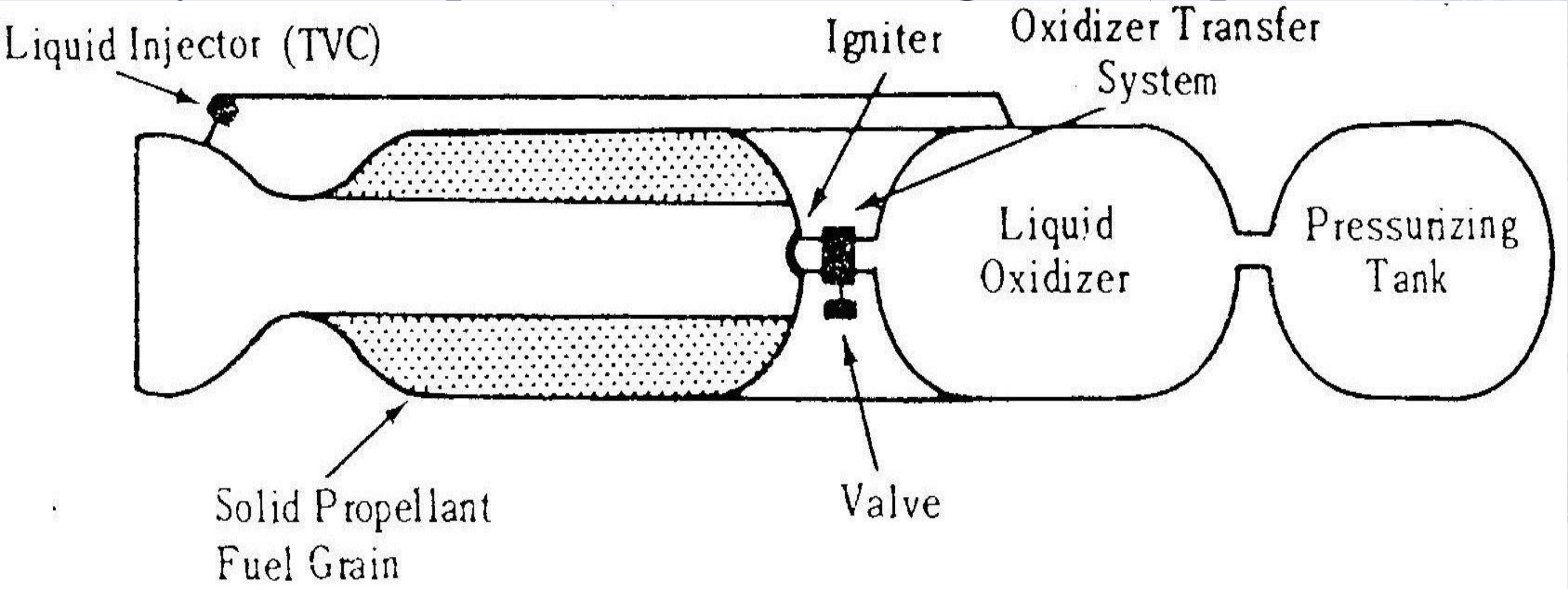
Multiple Hydrazine Thrusters connected to common propellant tanks provide attitude (roll, pitch, & yaw) as well as orbit correction (east / west)





Cold Gas Propulsion (even simpler) Gas (stored as liquid – like camping gas bottle) expanded via plenum chamber to provide easily controllable, but low thrust.

Hybrid Propellant Rocket Engines (liquid / Solid)



Pressurised tank of oxidiser feeds oxidiser to chamber containing solid fuel.

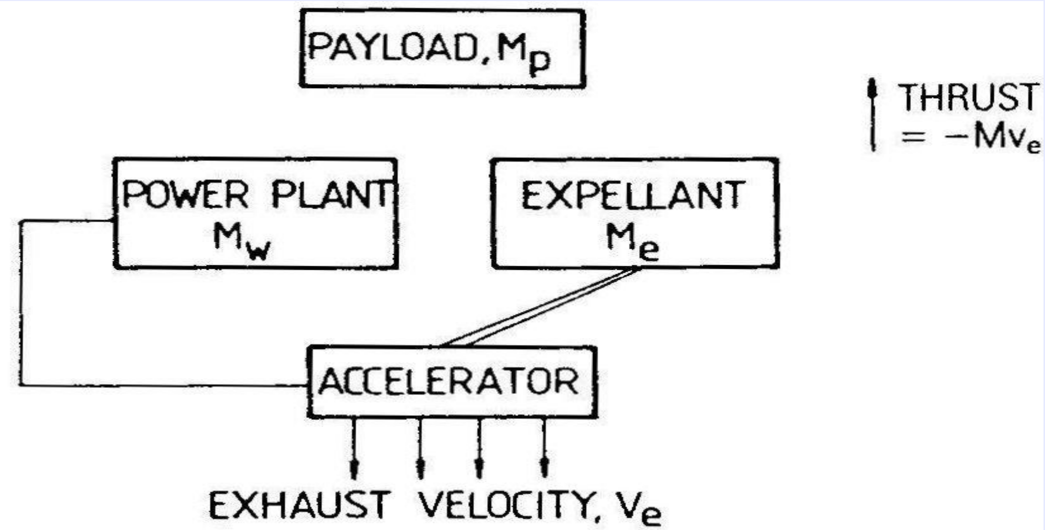
Advantages: easier to control than solid, simpler than liquid only bipropellant

Disadvantages: Large solid combustion chamber & thicker tank walls need to withstand higher pressures – poor MR → only medium Isp

Thrust Vector Control: Small directional changes by addition of propellant to side of nozzle (water tap example). Also used on large solids (Ariane5, Shuttle)

Uses: Few to date- primarily amateur rocket societies

Non-Chemical Rockets- General Accelerated Expellant

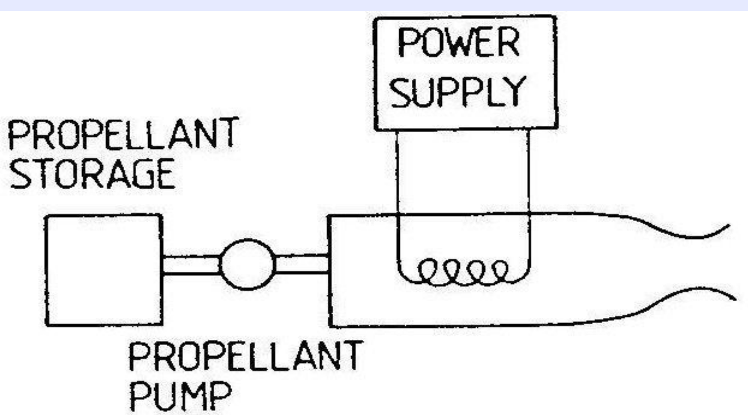


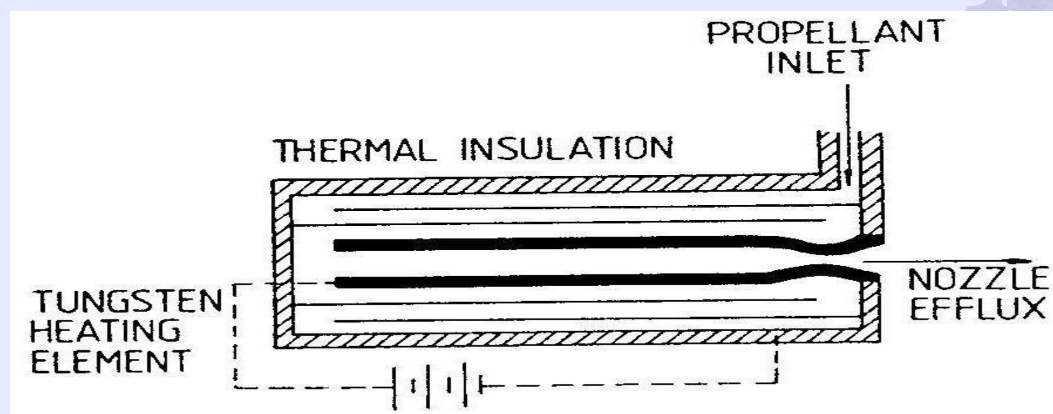
Accelerating an expellant and exhausting in one direction provides thrust in the opposite direction as per Newton's Law

Action = Reaction

Non-Chemical Rockets(1) : Resistojet or Arcjet

Electrical heater or electric arc heats up propellant/expellant, converting from liquid to gas and further heating gas expanding to accelerate. Only very low exhaust velocities, and low Isp. Very simple. Can also be made with nanotechnology for micro/nano satellites.





Non-Chemical Rockets(3): Nuclear Rocket

Expellant accelerated by heat of a nuclear reactor located in thrust chamber.

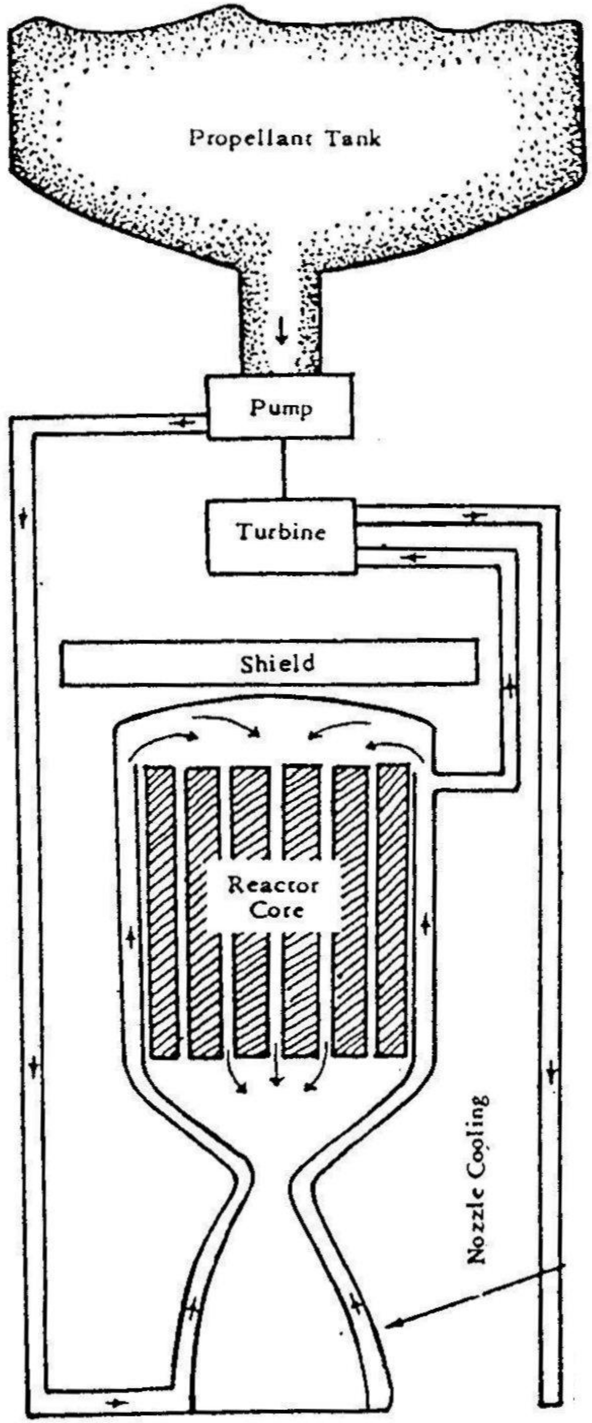
Expellant (e.g. liquid H2) pumped to thrust chamber- used to regeneratively cool chamber, then passed through reactor- hot gas expands through nozzle to high velocities.

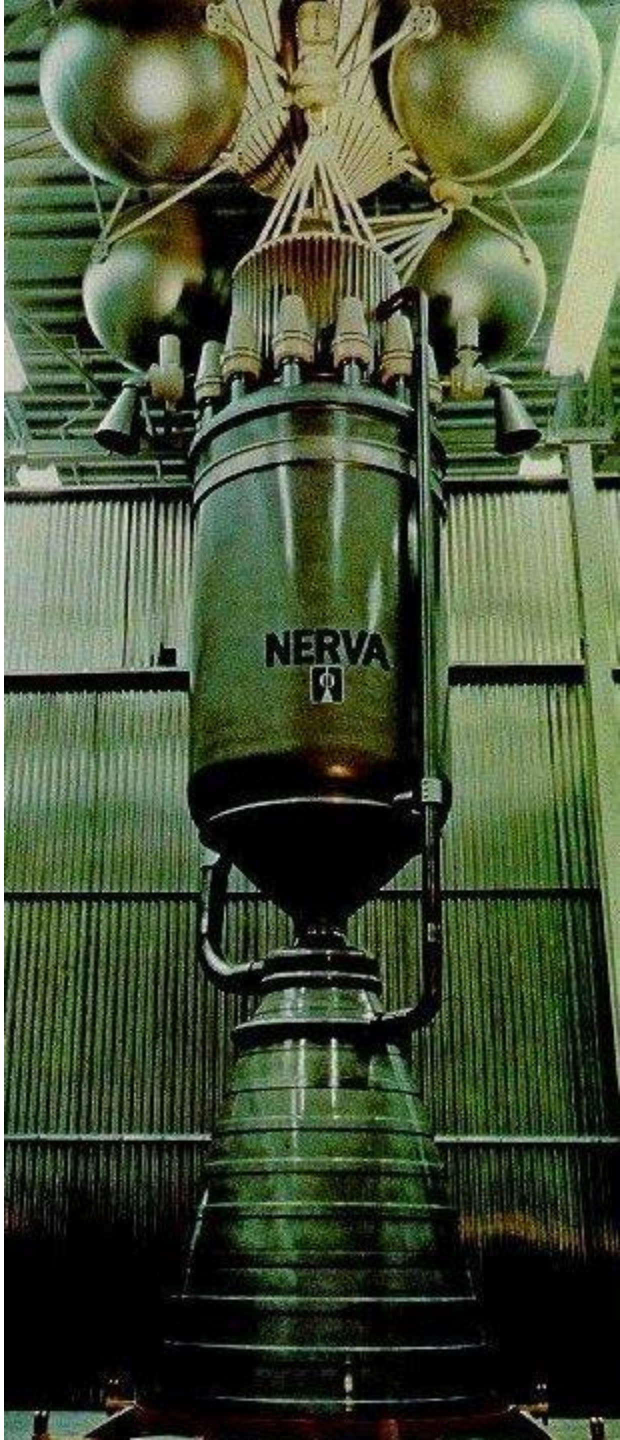
Very high Isp.

Very dangerous if propellant flow interrupted →reactor not cooled!!

Disaster if crashes→not practical/safe for launch!!

Nerva rocket engine was actually tested on gound!!!





Non-Chemical Rockets (2): Ion Engines

Ion Engines use a propellant with high mol. mass and low ionisation level- e.g. Caesium, Xenon. Liquid is vaporised, then ionised by electrons from heated cathode or by microwaves. Magnetic field keeps electrons gyrating to improve ionisation.

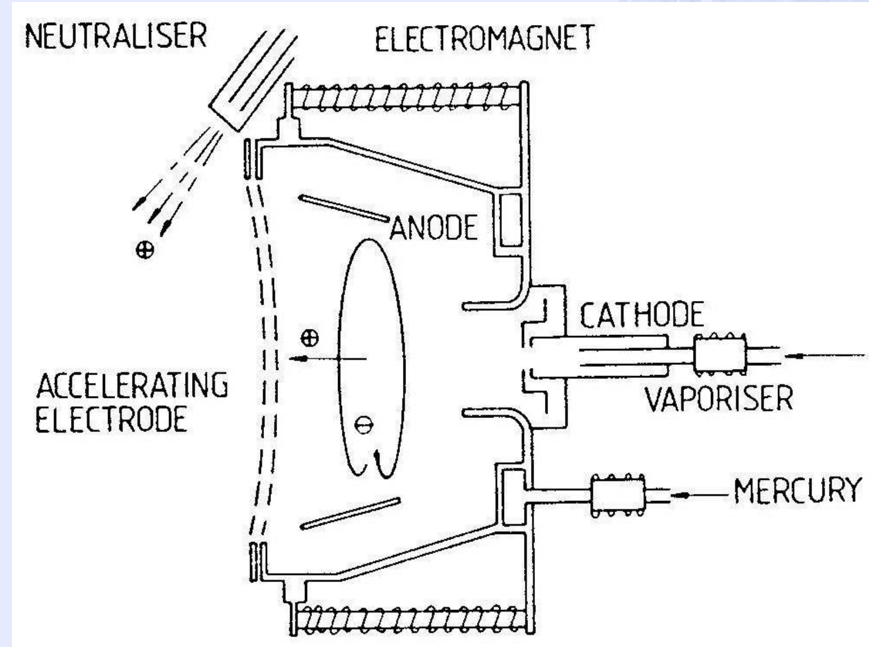
Ions are accelerated to high exhaust velocities by electrostatic field. Electrons emitted to neutralise exhaust.

Very high Isp (> 10 x chemical rockets)

Very low thrust (mN) (=weight of A4 sheet)

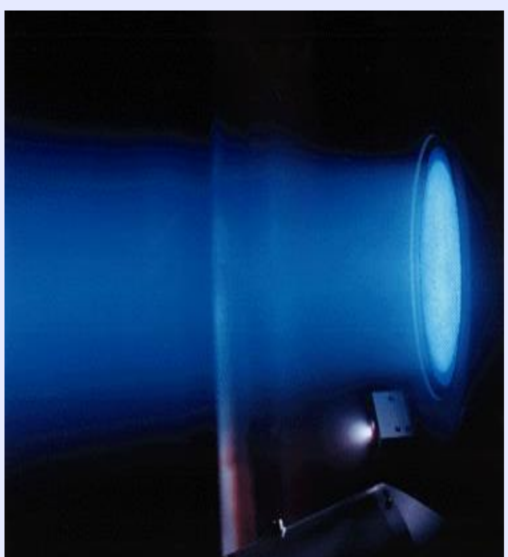
Uses: attitude & station keeping

Example of 10cm diameter thruster:

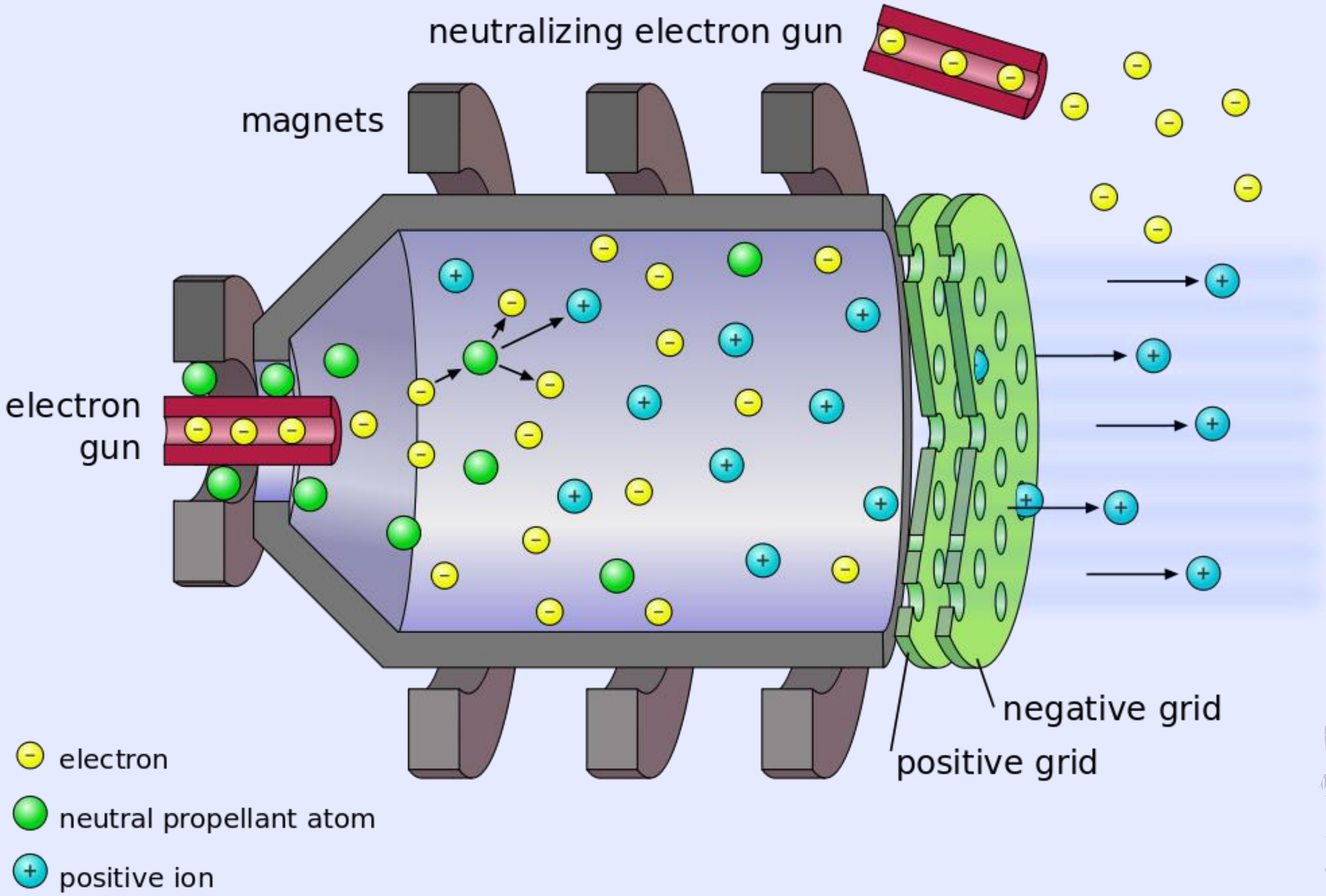


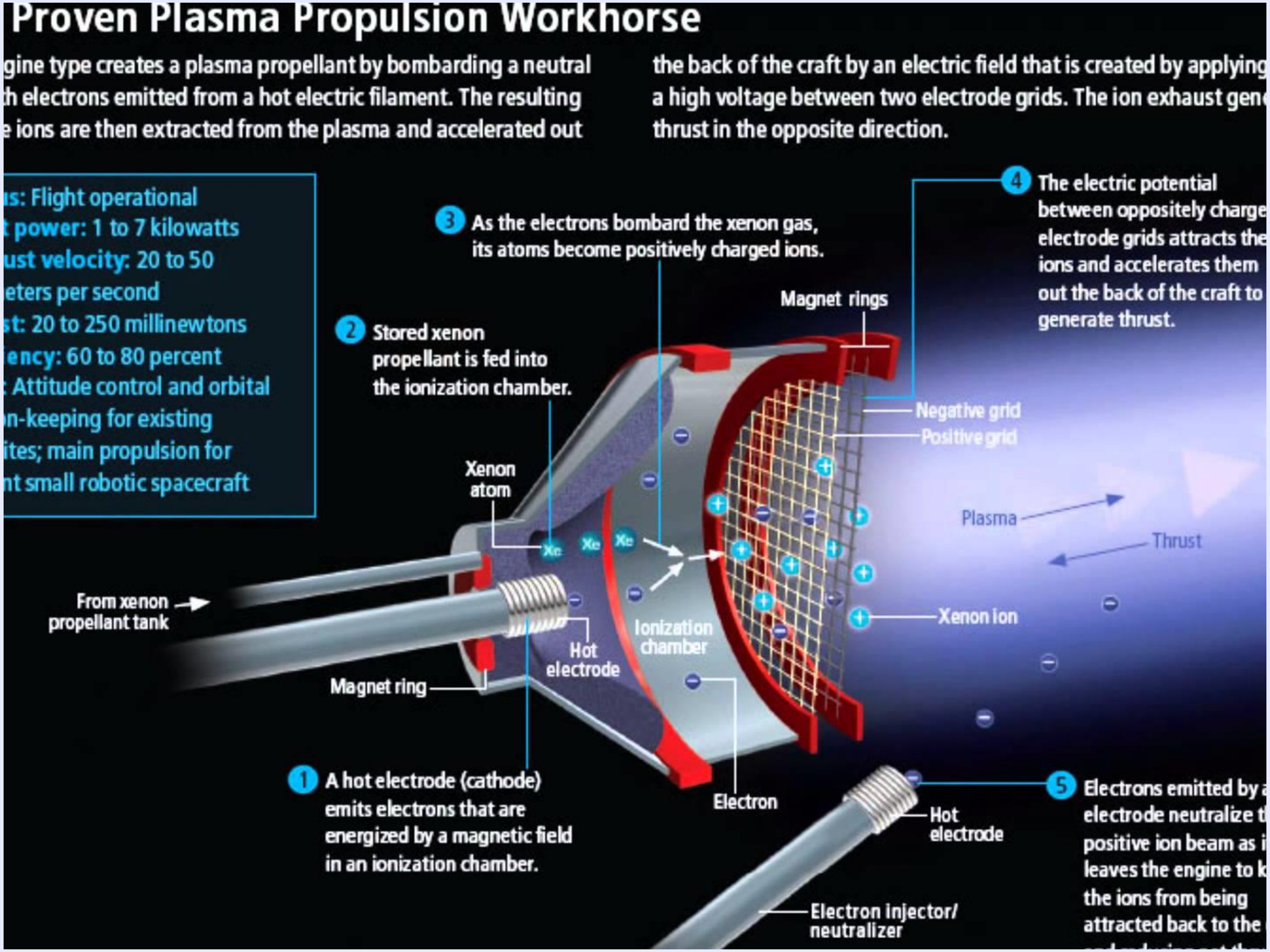
THRUST	10 mN
EXHAUST VELOCITY	30 km/s
ION BEAM CURRENT	160 mA
FRACTION OF PROPELLANT ACCELERATED INTO BEAM.	0·87
ENERGY EXPENDED IN PRODUCING AN ION IN THE EXHAUST (EXCLUSIVE OF THE ACCELERATION ENERGY).	245 eV/ion
ANODE POTENTIAL	42 V
DISCHARGE CURRENT	1·0 A
OVERALL ELECTRICAL EFFICIENCY	0·74
ELECTRICAL POWER	230 W

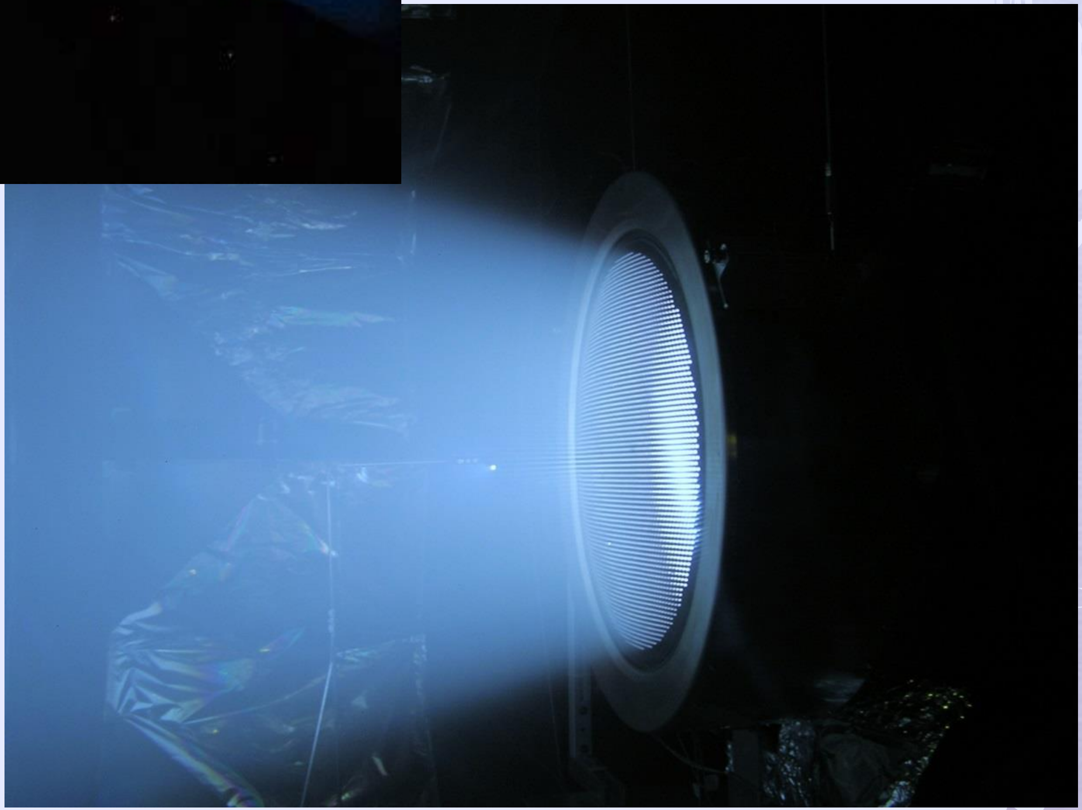
ESA SMART-1 at the Moon



Ion Thruster




Proven Plasma Propulsion Workhorse
gine type creates a plasma propellant by bombarding a neutral
h electrons emitted from a hot electric filament. The resulting
e ions are then extracted from the plasma and accelerated out
the back of the craft by an electric field that is created by applying
a high voltage between two electrode grids. The ion exhaust gen
thrust in the opposite direction.
s: Flight operational
t power: 1 to 7 kilowatts
ust velocity: 20 to 50
eters per second
st: 20 to 250 millinewtons
iency: 60 to 80 percent
: Attitude control and orbital
n-keeping for existing
ites; main propulsion for
nt small robotic spacecraft
3 As the electrons bombard the xenon gas, its atoms become positively charged ions.
4 The electric potential between oppositely charge electrode grids attracts the ions and accelerates them out the back of the craft to generate thrust.
2 Stored xenon propellant is fed into the ionization chamber.
Magnet rings
Negative grid
Positive grid
Xenon atom
Xe
Plasma
Thrust
From xenon propellant tank
Hot electrode
Ionization chamber
Xenon ion
Magnet ring
1 A hot electrode (cathode) emits electrons that are energized by a magnetic field in an ionization chamber.
Electron
Hot electrode
Electron injector/ neutralizer
5 Electrons emitted by a electrode neutralize t positive ion beam as i leaves the engine to k the ions from being attracted back to the



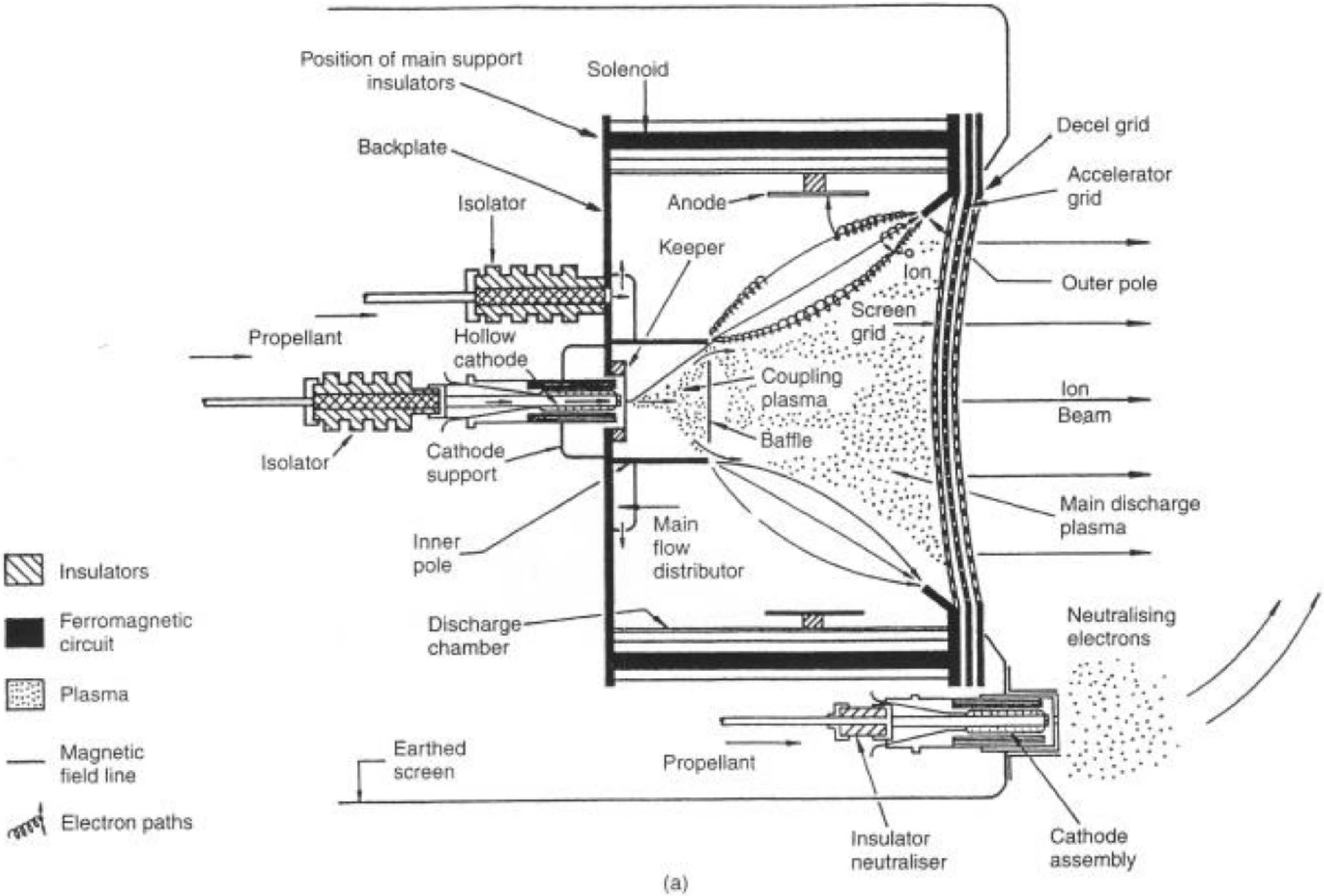


Figure 6.28 Typical ion thruster

The speed of light

- https://www.youtube.com/watch?v=0f7ycO7g5zI
- What are the possible technologies that will allow us to travel the Universe

The End